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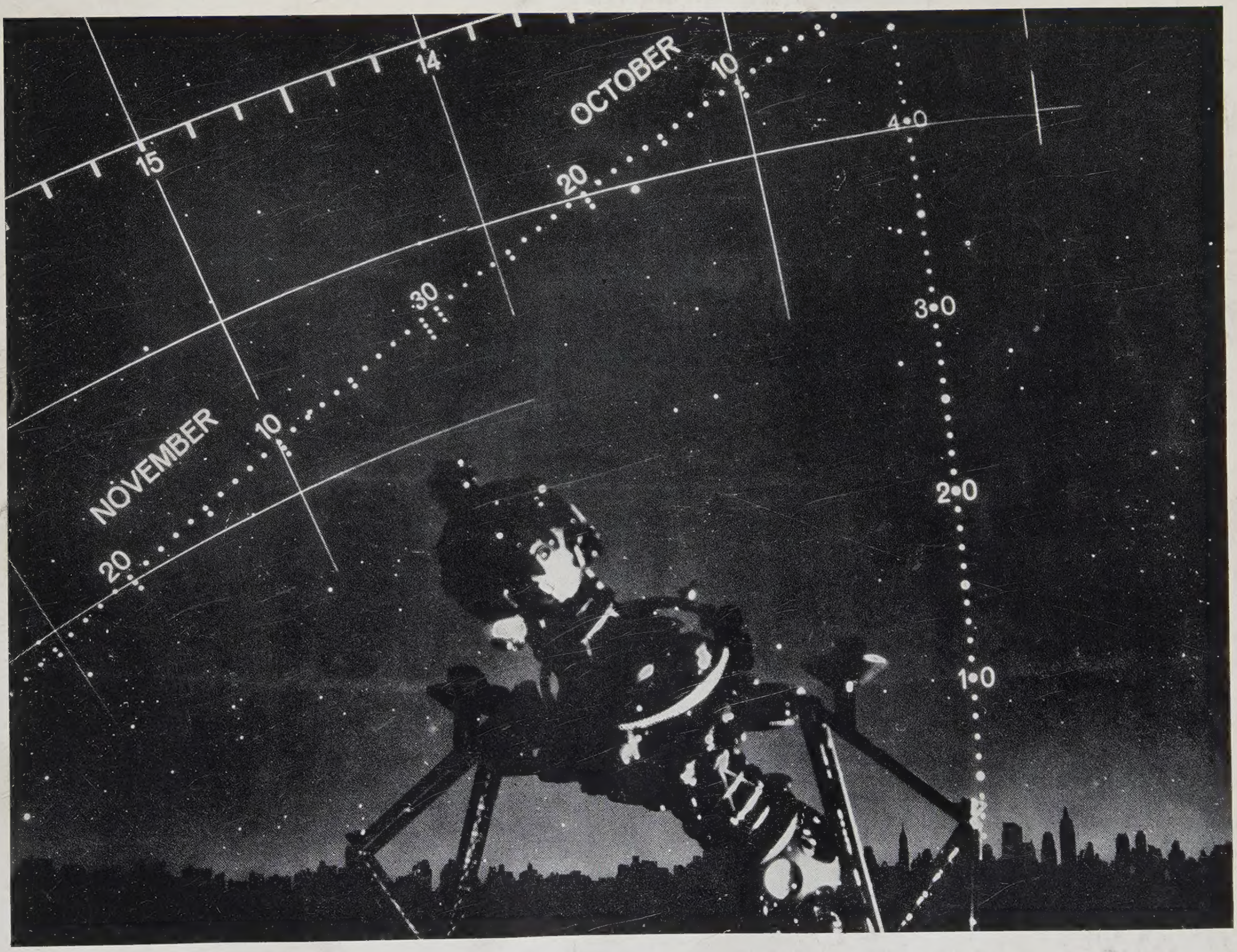

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Front Cover

Hayden Planetarium at the American Museum of Natural History in New York, N. Y., showing the Carl Zeiss projector in operation. The planetarium, on the list of inspection trips for the A.I.E.E. winter convention to be held in New York, January 28–31, 1936, promises to be of particular interest to many members

Photo by Wurts Bros., New York, N. Y.

Special Articles

A.I.E.E. Papers

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In This Issue—

LIGHTNING protection of electric power transmission and distribution systems constitutes the principal subject matter of 5 papers in this issue. Two of these papers have been prepared by subcommittees of the A.I.E.E. committee on power transmission and distribution: One presents a survey of methods now in use to reduce the effects of lightning on medium and high voltage lines (*pages 12–18*); the other discusses available methods of protecting transformers against both traveling waves and direct strokes (*pages 53–6*). A third paper reports operating results obtained by 38 companies with the newer methods of protecting distribution transformers, and is based upon a survey conducted by the Edison Electric Institute (*pages 47–53*). A fourth paper presents the results obtained with the interconnection method of protecting distribution transformers and equipment in a typical large urban system (*pages 63–70*). The remaining paper of the group presents a brief review of the history of lightning arresters and a discussion of factors affecting the economic application of arresters to electric power systems (*pages 84–93*).

REMOTE metering and remote indication schemes, combined with schemes for remote control, such as supervisory control or automatic load control, are being applied for an increasingly large variety of purposes. In one installation, remote metering and automatic control of load on a distant hydroelectric plant have greatly improved power system operation; a feature of this scheme is that constant beat frequency is maintained in the receiving apparatus, the transmission frequency being varied (*pages 40–7*). Also, a typical municipal waterworks system had supervisory control applied to it in conjunction with electric pump drive, resulting in greatly improved operation, and in a reduction in operating costs (*pages 36–40*). On the electrified section of a large railroad, several types of supervisory control and remote metering have been installed, and have been of considerable assistance in load dispatching and substation operation (*pages 70–05*).

A COMPENSATED thermocouple ammeter was developed a number of years ago as the result of an investigation of the thermal relations in instrument shunts and in conductors. The temperature distribution and heat flow were subjected to a mathematical analysis, and from this the theory of the electrothermic ammeter of the thermocouple type has been developed (*pages 23–33*).

RADIO TELEPHONE communication at ultra-high frequencies has been shown by tests to provide a highly satisfactory means of signaling between the locomotive cab and the caboose of a freight train. Frequencies of 30 to 40 megacycles were found to be quite satisfactory for this service. Transmitter power of 15 to 25 watts is believed to be sufficient for trains 200 cars or less in length (*pages 109–13*).

FINAL announcements for the 1936 A.I.E.E. winter convention to be held January 28–31, have been made. Supplementing the technical program for this convention, as announced in ELECTRICAL ENGINEERING for December 1935, pages 1408–09, social and entertainment features, medal presentation, inspection trips, and final changes in the technical program are reported herein (*pages 114–16*).

HIGH speed relays, now available for the protection of power transmission lines, have revolutionized the art of line protection. Such relays, operating in one cycle or less, especially when used with high speed circuit breakers, have many advantages. Existing relay systems frequently may be modernized by the addition of the new relays to the present relay schemes (*pages 56–62*).

POWER distribution systems, like other forms of engineering apparatus, have been considerably improved in recent years. Economy, better service, greater safety, and better appearance are among the results of the many improvements in system design and in details of equipment and construction which have been produced (*pages 75–84*).

AUTOMATIC control for steel-tank mercury-arc rectifiers has been developed to a high state of perfection. A review has been made of present day practice in automatic control, which includes the various unit auxiliaries as well as the equipment used primarily for switching (*pages 100–09*).

IN THE passing of Dr. E. W. Rice, Jr., the Institute loses another of its list of outstanding men, famous as pioneers in the now great electrical industry. Doctor Rice, a past-president of the Institute, was among its most highly respected, and most loved members (*pages 118 and 125*).

ELECTRICAL characteristics of sliding contacts between carbon or graphite brushes and copper slip rings are shown by experiment to be dependent upon the oxide film that forms on the surface of the rings (*pages 94–100*).

WHAT is electricity? Man has attempted to answer this question ever since the earliest discovery of electrical phenomena. A historical résumé of these attempts is presented in this issue (*pages 4–11*).

PERMANENT magnet materials have been developed recently with characteristics radically different from those of older materials, making available high specific magnetic performance in the low cost field (*pages 19–23*).

CELEBRATION of the 50th anniversary of the first commercial a-c system in America is to be made on March 20, 1936. Plans for a nationwide celebration are being made by the recently appointed committee (*pages 119*).

AUDIO transformers for high power radio-broadcast stations are fundamentally similar to 60 cycle power transformers, but differ in some important respects (*pages 34–6*).

Looking Forward

—A Message From the President

THIS issue of ELECTRICAL ENGINEERING ushers in a New Year for the electrical industry. While this is a fitting occasion to extend good wishes and to make good resolutions, it seems to me that it is a time, also, when we should pause for a moment to take our bearings.

For many, the depression, which is still with us, has been a time of acute mental and financial stress; but as concerns the engineering profession as a body, the benefits appear to outweigh the evils by a wide margin. Under the spur of necessity, which, after all, is the only force which drives man to do an outstanding job, the engineering profession has been doing highly effective work.

At whatever branch of the profession you may look you will find the same general picture. While the economic machine has been stalled the engineers have carried on research to find more efficient ways to utilize the materials and the forces with which they work, and there is no doubt that this activity will yield an enormous return. The scientific mind cannot be stopped in its search for truth. In spite of unfavorable economic conditions and reduced appropriations, it will continue its groping toward the light.

We cannot, of course, hope for a return of the so-called prosperity of 1929 nor should we wish it. That prosperity was built upon the wrecks of the Great War and it is my hope that we shall never see its like again. Most of us will be happy to achieve the sound prosperity which comes from earning only a fair return on our capability and effort.

Having accepted that philosophy we can take a fresh grip on our problems and resolve in this new year to push forward in the work of their solution.

The leaders in the engineering field are making ready for effective action in the coming year. They have taken inventory, analyzed causes, and know what has to be done. They are really the doers, the creators, the men who turn the wheels of industry. They know from hard experience the wide difference between theory and practice. They know that technical progress demands infinite patience in adjusting differences between paper plans and workable realities. Furthermore, they are aware that social progress is always a compromise between technical perfection and human nature.

It is not that the men of the engineering profession are lacking in ideals or principles. On the contrary, their standards are as high as, or higher than, those in any other walk of life. But necessity has schooled them to deal with life and with human nature as they are, to distrust inexperience and to center their attention on what is practicable.

What they have accomplished during the past 5 years is an effective demonstration of untiring perseverance in the face of great discouragement.

The engineering profession, strengthened by unification through its national societies, has played and will continue to play an important part in the industrial, governmental, and commercial affairs of the nation. Scientific achievement persists at an accelerated pace, and as each improvement is accomplished it is fitted into the already complex pattern of our existence.

The members of these societies through exchange of information and experience, and co-ordination of effort are placed in a position to accept the responsibilities of leadership. That leadership must be exercised with the utmost fairness and honesty, and in the common interest. It must take cognizance of the problems of the day while at the same time looking ahead toward the formulation of sound long term policies.

The degree of success achieved by the individual engineer during the coming year will depend entirely upon his own initiative. The ingenuity and scientific skill employed to effect successful conclusions will be a tribute to his competitive spirit. His application of energy and judgment will determine the extent of his contribution toward progress in his particular field of endeavor.

We can find inspiration in looking back over the past years and in tracing the remarkable progress of the electrical industry. The colorful sequence of technological discoveries and developments since the early days in the electrical field stimulates the imagination, arouses enthusiasm, and revives the spirit, vision, and courage of its pioneers.

May you be inspired by those wonderful accomplishments to strive for still greater progress in the future. And, in thus striving, may your coming year be most happy and prosperous.

E. B. Meyer

"What Is Electricity?"

By PAUL R. HEYL, Fellow Am. Phys. Soc.

National Bureau of Standards, Washington, D. C.

This address,[1] tracing the interesting history and significance of the many concepts of electricity as they have evolved from an indefinite beginning through the extremely rapid developments of the current century toward a speculative future, is republished here at the request of the Institute's committee on education.

I TRUST that no one is so optimistic as to suppose that because I have asked this question ("What is electricity?"[1]) I am going to answer it, nor so pessimistic as to fear that because I have asked a question which I cannot answer I can offer nothing but platitudes. I believe it possible in this case to avoid both Scylla and Charybdis.

"This question," said the late Professor John Trowbridge,[2] of Harvard University, "is often asked as though it were capable of a short and lucid answer which might be understood by any person of liberal education. Many answers have been given, but it is interesting to note that the more definite and confident the answer the older it is, and that as we ascend the ladder of time toward the present day such answers as we encounter are less definite and more cautious."

I think that it will be interesting for us to review, perhaps rather briefly, the ideas which have been held at various times as to the nature of electricity, and then, looking over the wealth of physical discovery which has been amassed in the past 40 years, to endeavor to select from it such facts as may be of importance in guiding and controlling future speculation on this question; for though such speculation has been at a minimum, if not a standstill, during the twentieth century, it will doubtless revive again. Speculation or as it has been otherwise termed, "apt conjecture, followed by careful verification," has been behind much of the advance of science. Such was the method of Faraday and of Darwin. The conjectures of the ancients, having little in the way of observed fact to guide them, might range far and wide, and had small heuristic value, but with the growth of experiment the range of conjecture has continually narrowed and its value as an aid to farther progress has steadily increased.

The beginning of our knowledge of electricity is lost in the mists of antiquity. What we can recover of it is excellently told by Park Benjamin in his history entitled, "The Intellectual Rise in Electricity."[3] It is customary to credit Thales (600 B.C.) with the first observation of the attractive power of rubbed amber, but Benjamin shows that amber was widely known among the ancients for centuries before Thales. Beads of amber have been found in the ancient lake dwellings of Europe in the royal tombs at Mycenae (2000 B.C.) and throughout northern Italy. The identity in chemical composition of these relics with the amber of the Baltic seacoast is significant of the esteem in which this substance was held and of the distance over which it was thought worth while to bring it. The golden glow of the polished beads suggested the beaming sun, called by Homer ἠλέκτωρ, which doubtless gave rise to the Greek name for amber, ἤλεκτρον.

It is incredible, as Benjamin points out, that this widespread acquaintance of the ancients with amber should have existed so long without its electrical property being often noticed. It is probable that Thales but shared the knowledge of his time in this respect, for his acquaintance with the things of nature in general was such as to enable him to make the first recorded prediction of an eclipse of the sun. Thales left no writings of his own, and all we know of him we have learned from those who lived several centuries later.

It appears from these authorities that the ancients regarded electricity as a soul or spirit resident in an otherwise lifeless substance. This was in harmony with the prevailing thought of the times, which regarded all motion as evidence of life. The air was inanimate, but the wind was the breath of Aeolus; the waves of the sea were excited by the wrathful strokes of Neptune's trident; the lightning was the thunderbolt of Zeus. This animistic explanation of the nature of electricity was simple and definite enough to be understood by anyone, and lasted for several millenniums; in fact, until the revival of learning and the growth of experimental science supplied material upon which to base a rival theory.

We are helped to realize this animistic point of view when we read in a translator's footnote to Gilbert's book on "The Magnet"[4] that a certain ancient physician recommended the administration of doses of powdered lodestone in cases of estrangement between husbands and wives. Given the premises of the time, such a conclusion was perfectly logical. It was obvious that the patients exhibited a deficiency of a certain spiritual element which was found in the lodestone, and the adminstration of that medicine followed as naturally as a modern prescription of cod liver oil because of its vitamin content.

It was the middle of the sixteenth century before the next answer on record was given to the question, "What is electricity?" This answer came from

1. The fifth Joseph Henry Lecture, delivered March 30, 1935, before the Philosophical Society of Washington (D. C.) in honor of its first president. Published: *Journal*, Washington Academy of Sciences, v. 25, 1935, p. 201; *The Scientific Monthly*, July 1935, p. 38. Republished in ELECTRICAL ENGINEERING with the approval of the National Bureau of Standards of the United States Department of Commerce, and of the author and other interested parties.

2. Trowbridge, "What Is Electricity?" London: Kegan Paul, Trench, Trubner and Co., 1897.

3. London, Longmans, Green and Company, 1895.

4. Translation by P. Fleury Mottelay, N. Y., John Wiley and Sons, 1893, page 56.

5. Cardan, *De Subtilitate*, Lib. XXI, Paris, 1551.

Cardan,[5] whose name is familiar to mathematicians (perhaps more so than it deserves to be). Cardan was the originator of the fluid theory of electricity which held the stage in one form or another for more than 3 centuries, and survives today in popular parlance in the term "the electric fluid" or, still more colloquially, "the juice." Cardan passed from the spiritual to the material in his explanation, which was that amber "has a fatty and glutinous humor which, being emitted, the dry object desiring to absorb it is moved towards its source, like fire to its pasture; and since the amber is strongly rubbed, it draws the more because of its heat."[6]

In this last sentence we see the influence of Cardan's profession. He was, among other things, a physician, and was accustomed to warm the cupping glass in drawing blood from his patients. The laws of pneumatics were not yet understood at that time, and it was generally supposed that the cupping glass acted because of its heat.

The fact that this "fatty and glutinous humor" was intangible and invisible seems to have caused Cardan no embarrassment. We may perhaps view this the more charitably when we think of the contradictory attributes that later scientists have found it convenient to assign to the luminiferous ether.

The year 1551 in which Cardan published this theory may be taken as marking the end of the first era, in which electricity was regarded as a soul or spirit. Its beginning goes back beyond recorded history.

The concept of electricity as a material substance contained in certain bodies known as electrics was strengthened by the experiments of Gilbert (1600), who showed that many substances besides amber were to be included in this class, but the full development of the fluid theory of electricity did not come until the middle of the eighteenth century. In the meantime, von Guericke (1672) had invented his sulphur globe electrical machine, which made electrical experimentation easy on a large scale. With the facilities thus placed at his disposal he discovered electrical conduction and electrostatic repulsion, the latter destined to be a phenomenon of prime importance in later speculation on the nature of electricity.

In the eighteenth century development of the fluid theory 2 names are prominent, those of Du Fay and Franklin, each typifying a separate trend in theory.

Du Fay's experiments (1733 and later) chronologically preceded those of Franklin. His most important discovery was that glass when rubbed behaved in one respect quite differently from amber; a bit of gold leaf excited by contact with the glass tube is then repelled by the glass but attracted by excited amber. "And this," said Du Fay, "leads me to conclude that there are perhaps 2 different electricities." These he distinguished accordingly as vitreous and resinous, and laid down the law that like electricities repel each other and unlike attract.

To explain the same phenomenon Franklin (1747) postulated a single electric fluid of which all bodies were normally full. If a body acquired more than this normal amount he called it "plus," or positively electrified, and if its charge was less than normal, "minus," or negatively electrified.

Franklin's hypothesis had simplicity in its favor; it required one less assumption than that of Du Fay. In this respect it obeyed more closely the rule laid down by Newton: "We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances . . . for Nature is pleas'd with simplicity and affects not the pomp of superfluous causes."[7]

This simplicity of Franklin's hypothesis, added to the reputation which he himself rapidly attained in scientific circles, gave the one-fluid theory an advantage over its competitor for the time being, but a serious theoretical objection was soon raised against it. Since on this theory a negative charge meant a deficiency of electric fluid, there must be a limiting value of negative charge, namely, when the body is completely emptied of the electric fluid; but 2 such bodies, both being negatively charged, should repel each other—and why?

There was much hesitancy on the part of the one-fluid advocates about pushing this argument to its logical conclusion. It remained for a bold German named Aepinus (1759) to seize the bull by the horns and assert that matter devoid of electricity is self-repellent.

This doctrine came as a shock to a generation many of whom could remember Newton. It was useless to point out that Newton had deduced the law of gravitation by observation of bodies that possessed their normal amount of electricity, and that the behavior of matter with the maximum negative charge was something which no one had ever observed. The one-fluid theory had received a serious jolt from which it never recovered; this argument was used against it as late as the 1830's. The attention of theoretical physicists of the eighteenth century was turned toward the 2-fluid theory, and during the closing years of that century and the early part of the nineteenth the work of Coulomb, Laplace, Biot, and Poisson produced an elaborate and elegant mathematical theory which so well described all the electrostatic phenomena then known that by 1830 the 2-fluid theory was generally accepted.

But it often happens that as soon as one theory is comfortably settled on the throne another rises up to challenge its supremacy. We shall see the reign of each successive theory of electricity growing shorter. The thousands of years of the first era were followed by three centuries of the second. In the first half of the nineteenth century great things were happening. In 1820 Oersted had discovered that an electric current could produce a magnetic effect, thus tying together what had previously been regarded as separate phenomena. In 1822 Seebeck showed that electricity could be generated by heat. These discoveries impressed themselves on the mind of Faraday, then at work in the Royal Institution. He was familiar with the work of Davy in producing chemical decomposition by electricity, and the converse phenomenon of Volta, the production of electricity by chemical action. Faraday was also aware of the converse of Seebeck's discovery, the production of heat (and light) in the electric arc, and his

6. Park Benjamin, *op. cit.*, p. 248.

7. Newton, "Principia," Book III: "Rules of Reasoning in Philosophy."

thoughts turned naturally toward the undiscovered converse of the Oersted effect. He says himself at a later time[8] (1845): "I have long held an opinion almost amounting to conviction, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or in other words, are so directly related and mutually dependent, that they are convertible, as it were, into one another, and possess equivalents of power in their action. In modern times the proofs of their convertibility have been accumulated to a very considerable extent, and a commencement made of the determination of their equivalent forces."

Such were the considerations which led Faraday to attempt the generation of electricity by means of a magnet (1831). The story is familiar to all of us; how he placed a magnet in a helix of wire and found that no current was produced except momentarily while the magnet was being placed in or taken out of the coil. This discovery seems to have made quite an impression in other than scientific circles, as is evidenced by some verse which has come down to us:

Around the magnet, Faraday
Is sure that Volta's lightnings play.
To bring them out was his desire.
He took a lesson from the heart;
'Tis when we meet, 'tis when we part,
Breaks forth the hid electric fire.

Encouraged by this success, Faraday later (1845) sought and found a correlation between magnetism and light. Twenty years later this in its turn furnished the inspiration for Maxwell's electromagnetic theory, by means of which the domain of optics was annexed to that of electricity

The publication of Maxwell's paper in 1865 may be considered as closing the second era of electrical theory, that in which electricity was regarded as a material fluid, and the opening of the third era in which the concept of electricity assumed a less material and more elusive form.

By 1865 the 2 great doctrines of nineteenth century physics, the conservation of energy and the correlation of physical forces (as foreshadowed by Faraday) had been enunciated and were well on the way to general acceptance. During the '70's and early '80's electricity, in common with heat and light, was sometimes called, in the phrase of the day, "a mode of motion," which meant a form of energy.

The adoption of this view was, of course, a matter of slow growth. Maxwell's electromagnetic theory had a long struggle for acceptance; so long, in fact, that Maxwell himself did not live to see its final triumph. He died in 1879, and it was not until 1886, when Hertz produced experimentally the electromagnetic waves which Maxwell's theory demanded, that its acceptance may be said to have become complete.

Against this concept of electricity as a "mode of motion," that is to say, a form of energy, Lodge[9] in 1889 entered a protest. He pointed out that water or air under pressure or in motion represents energy, but that we do not therefore deny them to be forms of matter. He emphasized an important distinction between 2 terms: *electrification*, which is truly a form of energy, as it can be created and destroyed by an act of work; and *electricity*, of which none is ever created or destroyed, it being simply moved and strained like matter. "No one," said Lodge, "ever exhibited a trace of positive electricity without there being somewhere in its immediate neighborhood an equal quantity of the negative variety."

Lodge did much to crystallize the ideas of the time concerning the nature of electricity. These ideas, since Maxwell's merger of optics with electricity, had been, as Lodge pointed out, not clearly defined, but in general the idea was that electricity was in some way a phenomenon of the ether. Lodge enlarged upon this idea, explaining electrostatic phenomena as due to ether stress, electric currents as ether flow, and magnetism as ether vortices. Electricity, which had been previously regarded as a material fluid, now became an immaterial one, and in consequence this third period of electrical theory may be called the ethereal era.

As we mount toward the present time we see the different eras of electrical theory rapidly shortening in duration. While the spiritual era lasted several millenniums and the fluid theory 3 centuries, the ethereal era lasted only a few decades. The fourth era is that which is still with us. It may be called the atomic or quantum period, in which it is noteworthy that but little attention has been paid to the ultimate nature of electricity and a great deal to its structure. It is difficult to say when this period began, as, in fact, the ethereal era began to die almost as soon as it began to live.

Wilhelm Weber,[10] in 1871, in developing his theory of magnetism, pictured to himself light positive charges rotating about heavy negative ones, much like a satellite about a planet; and in 1874 Johnstone Stoney read before section *A* of the British Association a paper entitled, "The Physical Units of Nature," which was not printed until 7 years later.[11] In this paper he asserted the atomic nature of electricity, and made a rough calculation of the elementary charge on the basis of Faraday's law of electrolysis. Ten years later[12] he was the first to use the term "electron."

Helmholtz,[13] in his Faraday lecture at the Royal Institution in 1881, further developed this line of thought, saying (page 290): "Now the most startling results of Faraday's law is perhaps this. If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions, which behave like atoms of electricity."

Maxwell himself saw that his electromagnetic theory was essentially continuous in its nature, and recognized the difficulty arising from the implications of Faraday's experiments. In his "Treatise on Electricity and Magnetism" (1873, Vol. 1, Chap. IV, page 313) in the chapter on electrolysis he says: "It is extremely improbable that when we come to understand the true nature of electrolysis we shall retain

8. Faraday, "Experimental Researches in Electricity," v. 3, p. 1, London, 1855.
9. Lodge, "Modern Views of Electricity," p. 7, London, Macmillan and Company, 1889.
10. Millikan, "The Electron," p. 20, Univ. of Chicago Press, 2nd edition, 1924.
11. Stoney, *Phil. Mag.*, v. 11, 381–390, 1881.
12. Stoney, *Sci. Trans. Royal Dublin Society*, v. 4, 1891, 11th series, p. 563.
13. Helmholtz, *Journal of the Chemical Society* (London), v. 39, 277–304, 1881.

in any form the theory of molecular charges."

For Helmholtz, however, the atomic nature of electricity was beyond question. Electricity, as he saw it, was a special chemical element[14] whose atoms combine with those of other elements to form ions. Moreover, it appeared to be a monovalent element, for it seemed that a monovalent element combined with one electron, a bivalent element with 2, and so on, exactly as a chlorine atom combines with one atom of hydrogen and an oxygen atom with 2 atoms of hydrogen. Helium, with its zero valence and double electrical charge, was as yet unknown.

The inevitable process of reconciliation of these contradictory theories was early begun by Lorentz,[15] who suggested for this purpose his electron theory of electricity. On this theory all the effects of electricity inside bodies were explained on the assumption of electrons, and all the effects of electricity at a distance—electrostatic, electromagnetic, and inductive—required the help of the ether. To unite these 2 classes of phenomena he assumed that each electron was closely bound up with the ether, and that any change in configuration of the electrons produced a change in the ether which was propagated with the velocity of light, and thus produced action at a distance.

About this time an entirely new line of experimental research was developing which was destined eventually to make the atomic concept of electricity dominant for a time. This was the study of the electric discharge in high vacua. Several workers had investigated this field without attracting much notice, but it remained for Crookes to direct widespread attention to this class of phenomena by an exhibition of novel and beautiful effects in vacuum tubes which he gave at the meeting of the British Association at Sheffield in 1879. Crookes unquestioningly assumed these effects to be due to electrified molecules of residual gas in the tube. It was shown later by others (J. J. Thomson, Townsend, Wilson, Millikan) that the negatively charged particles in a Crookes tube were not molecules or even atoms, but bodies of a minuteness previously unknown, about the $^1/_{1800}$th part of a hydrogen atom in mass, and bearing a definite negative charge of electricity. For these tiny bodies the term electron, introduced by Stoney, was revived. Still later work brought to light the proton, with an equivalent positive charge but larger mass than the electron and, in our own day, the positive electron.

As the result of this new line of investigation it became clear that a great many electrical phenomena required the atomic theory of electricity for their explanation. A great many, but not all; for a large number refused to fall in line under a corpuscular explanation, but could be simply and completely explained on Maxwell's theory as ether disturbances. The discovery by Hertz of the electromagnetic waves predicted by Maxwell did much to swing the pendulum back in this direction. The reconciliation of these contending views has been carried on much along the line originally taken by Lorentz. It is of interest to note that his idea of an electron inseparably bound up with the ether is found today in all essentials in the theory of wave mechanics.

We have now brought this somewhat hurried survey of electrical history up to the present day. We have seen that past speculations as to the nature of electricity fall into 4 classes, each corresponding to an era of thought. In the first of these eras, beginning probably with the earliest observations of electrical attraction and terminating in the middle of the sixteenth century, electricity was regarded as a soul or spirit. The second era may be said to have been opened by Cardan in 1551 and closed by Maxwell in 1865. During these 3 centuries electricity was regarded as a material fluid of one or 2 kinds. It is worthy of note that during this period the concept of the electrical fluid showed a trend toward the immaterial, from Cardan's "fatty and glutinous humor" to the impalpable and imponderable fluid of the early nineteenth century. In the third era electricity in its various manifestations was regarded as some kind of an ether disturbance of a continuous nature. The fourth concept emphasized the atomic or discontinuous structure of electricity without any suggestion as to the ultimate nature of these atoms.

Although speculation as to the ultimate nature of electricity has been in abeyance since the opening of the twentieth century, it will certainly arise again; and, within limits, it is well that it should. We may therefore turn now to an examination of the wealth of material which the last 40 years have placed at our disposal, and see what it may contain that is likely to be of importance in guiding and suggesting future speculation as to the nature of electricity.

The emphasis laid by the twentieth century on the structure rather than the nature of electricity is natural, for structure is much more easily determined than nature; moreover, a knowledge of the first is likely to give us some useful hints as to the second. It appears that the discontinuous structure of electricity goes almost hand in hand with that of matter. A tabular view of the known elementary particles of matter with their associated charges of electricity will be useful:

	Charge	+	−	0
Mass	Heavy	Proton	....	Neutron
	Light	+Electron	−Electron	(Neutrino)

The heavy particles now known—the proton and the neutron—have a mass equal to that of a hydrogen atom; the light particles have about $^1/_{1800}$ of this mass. The light neutral particle has not yet been discovered, but so urgent is the demand for it in current nuclear theory that it has been named before its advent.

According to the idea that has prevailed for 2 centuries, positive and negative electricity should be merely reflected images of each other, their properties being equal and opposite. The behavior of the negative electron and the proton shows nothing inconsistent with this concept as far as electrical properties go. On the discovery of the positive electron it was thought at first that it was shorter lived or, as a chemist might say, more reactive than its negative

14. Graetz, "Recent Developments in Atomic Theory," London, Methuen and Co., 1923.

15. Lorentz, *Verslagen en Mededeelingen der Koninklijke Akademie van Wetenschappen*, Amsterdam, v. 8, 323–327, 1891. Also *Archives Neérlandaises*, v. 25, Chap. IV, p. 432 *et seq.*, 1892.

16. Allowing for relative abundance.

counterpart, but this has not been borne out by subsequent investigation.[16] The mass associated with the positive charge in this case has been investigated by several persons. The latest work is that of E. Rupp,[17] who finds that the mass is within 5 per cent of that of the negative electron. Rupp appears to have found one point of difference between the 2 which, if confirmed, will be of importance.

It has been found that the passage of negative electrons through thin films of metal is accompanied by a diffraction effect, photographs of the electron beam after transmission showing a series of concentric rings. Rupp passed negative and positive electrons through the same films of gold and aluminum, and found that while the negative particles gave the usual rings the positive particles showed a continuous scattering. We will return to the interpretation of this later.

As to the neutron, it is still uncertain whether it is a proton which has acquired a negative electron or whether it is to be regarded as an independent entity without electric charge. The latter, as we shall see later, would be in serious conflict with present accepted electrical theory.

There was a time, not so very long ago, when the atom of matter was considered to be its ultimate structural unit. The discovery of the proton and the electron gave meaning to the term "sub-atomic." With this in mind, the question naturally arises as to a possible further subdivision of the electron. Several observers have claimed to have found evidence of smaller charges than that carried by the electron, but Millikan,[18] after an exhaustive discussion of the subject, came to the conclusion that up to 1924 there had been adduced no satisfactory evidence of this smaller charge.

In the early years of the present century there was some discussion as to whether the electron was to be regarded in shape as a rigid sphere (Abraham) or as contractile. The latter hypothesis was advanced by Lorentz to explain the negative result of the Michelson-Morley experiment. Lorentz supposed the electron, by motion through the ether, to flatten into an oblate spheroid. Experiments by Bucherer[19] in 1909 were interpreted as favoring the hypothesis of Lorentz.

But in 1927 a new line of experimental evidence as to the structure of the electron was opened by Davisson and Germer,[20] soon followed by G. P. Thomson.[21] These investigators found, in brief, that electrons (of the negative variety) might be scattered by reflection or diffracted by passage through very thin films of metal in such a way as to suggest that an electron is at least as much like a little bunch of waves as it is like a particle, and that neither aspect can be ignored.

This is well brought out by G. P. Thomson's diffraction rings. The electron must have a wave aspect, or there would be no interference pattern; it must have a charged particle aspect, or the whole ring system would not be deflected by a magnet, as it is found to be. The whole situation, in fact, had been foreshadowed theoretically by the wave mechanics of de Broglie and Schrödinger.

A number of explanations have been offered for this dual behavior. Perhaps the most completely worked out is that of J. J. Thomson,[22] based upon the diffraction rings obtained by his son, which lend themselves particularly well to theoretical treatment. On this view the electron is associated with and accompanied by a group of waves which guide and direct its motion. Now it was found by a study of the speed of the electrons and the associated wave lengths in the diffraction rings that a curious and complicated relation existed between these quantities. If u is the velocity of an electron and λ its associated wave length, this relation is:

$$\frac{u\lambda}{\sqrt{1 - u^2/c^2}} = C \qquad (1)$$

in which c is the velocity of light and C is a constant.

But this, as J. J. Thomson shows, is exactly the relation that should hold for the group speed of electromagnetic waves in a medium such as the Kennelly-Heaviside layer, containing a multitude of electric charges, positive and negative.

J. J. Thomson, therefore, suggests the following structure for the negative electron:

1. A nucleus which, like the older concept of the electron, is a charge of negative electricity concentrated in a small sphere.

2. This nucleus does not constitute the whole of the electron. Surrounding it there is a structure of much larger dimensions which may be called the sphere of the electron. This sphere contains an equal number of positive and negative charges, forming a little Kennelly-Heaviside layer around the nucleus. Measurements on the diffraction rings indicate a diameter for this sphere at least 10,000 times that previously accepted as the diameter of the electron.

3. The nucleus is the center of a group of waves and moves with the group speed in its atmosphere of electric charges.

At the time that J. J. Thomson proposed this hypothesis the positive electron was not known. Here comes in the importance of Rupp's work previously referred to.[17] On their face, these experiments indicate either that the train of waves that accompanies a negative electron is absent from the positive electron or that all possible wave lengths are present.

Just as the atom, once regarded as an ultimate structural unit, is now recognized as a complex of electrons, protons, neutrons, and possibly neutrinos, so the electron, it seems, must be regarded as a similar complex. Much more, doubtless, is to be learned about its structure before we can hope to answer the question, "What is electricity?"

But perhaps the most outstanding fact in modern physical theory is the dominant position occupied by electricity. In the nineteenth century one spoke of matter and electricity as separate and independent entities; nowadays electricity has become the fundamental entity of which matter is merely an aspect. Matter, once supreme, has lost its individuality and has become merely an electrical phenomenon of which electricity may exhibit more or less according to circumstances.

17. Rupp, *Phys. Zeit.*, v. 35, p. 999, 1934. But in *Zeit. für Physik*, v. 93, p. 278, 1935, Rupp has withdrawn his earlier article for revision.

18. "The Electron," Chap. VIII.

19. Bucherer, *Annalen der Physik*, v. 28, p. 513, 1909; v. 29, p. 1063, 1909.

20. Davisson and Germer, *Nature*, April 16, 1927; *Phys. Rev.*, v. 30, p. 705, December 1927.

21. G. P. Thompson, *Proc. Roy. Soc.*, v. 117, p. 600, February 1, 1928.

22. J. J. Thomson, "Beyond the Electron," Cambridge University Press, 1928; *Phil. Mag.*, v. 6, p. 1254, December 1928.

It is obvious that our answer to the question, "What is electricity?" will be fundamentally influenced according to whether we hold an electrical theory of matter or a material theory of electricity. It will therefore be worth our while to examine the foundation for the present view that electricity, whatever it may be, is the sole world-stuff. So radical has been this change in our thinking that it would seem a foregone conclusion that it must be based upon the clearest and most unequivocal of experimental evidence.

This change in our concepts did not come suddenly. Its beginning dates back to 1893, when J. J. Thomson[23] showed on theoretical grounds that a charged sphere in motion through the ether would encounter a resistance which to all intents and purposes would appear as an increase in the sphere's inertia, i. e., in its mass. Calculation indicated that this effect would become appreciable only if the velocity of the charged body was comparable to that of light.

In 1893 this suggestion was of academic interest only, no bodies moving with sufficient speed being then available for experiment. A few years later conditions had changed. The study of radioactive substances and of the discharge of electricity through gases had placed at our disposal positively and negatively charged particles moving with unprecedented speeds, which in the case of the negative particles were in some cases comparable with the speed of light. Here, it would seem, was an opportunity to test Thomson's theory of increasing mass.

Unfortunately, the conditions of the problem were such that it was not at first possible to obtain a measure of the mass of such a particle, but only a determination of the ratio of the electric charge to the mass which carried it (e/m).

Kaufmann[24] found, however, that for the swifter particles this ratio was less than for the slower ones. There were only 2 ways of explaining this fact, both equally radical: either the mass increased or the charge diminished as the speed of the particle became greater.

In this dilemma, opinion inclined generally to the first alternative, largely because there was in existence a theoretical reason to expect it, while no one as yet had been ingenious enough to suggest any reason why a moving charge should alter. It is of importance to note that Kaufmann's experimental result, because of its equivocal character, cannot be accepted as more than half proving J. J. Thomson's theory.

Kaufmann calculated that such particles as he experimented with might have, when moving slowly, an "electrical mass" equal to about $^1/_4$ their total mass. In making this calculation he assumed that a particle behaved as though it were a little metallic conductor, but he was careful to point out that a different assumption might lead to another result.

And so it happened. J. J. Thomson, on the assumption that a particle had no metallic conductivity, but acted like a point charge, found that Kaufmann's results indicated that the whole of the mass of the particle might be accounted for electrically.

This was the origin of the electrical theory of matter. Its pedigree goes back to J. J. Thomson's theory, which in turn was derived from the electromagnetic theory of Maxwell. Kaufmann's experiments only half proved Thomson's theory, which in addition was complicated by a special assumption with regard to the distribution of the charge on the particle. Without this assumption only a part of the mass could be accounted for electrically.

But much water has run under the bridge since 1893. Forty years is a long life for any physical theory in these days, and the recent discovery of the neutron has brought with it a challenge to the electrical theory of matter.

In J. J. Thomson's original theory of the increase in mass of a moving charge, it was an essential point that the lines of force should be free to adjust themselves as the motion demanded. As a leaf or a card tends to flutter down through the air broadside on, so the lines of force, originally distributed radially and symmetrically about the charge at rest, will tend to set themselves in a plane perpendicular to the direction of motion of the charge. They will not all be able to lie in this plane because of their mutual repulsion, but the density of the lines will be a maximum in this plane and a minimum in the direction of motion, and a certain space distribution will result, of such a nature that the apparent increase of mass can be completely accounted for.

But it is essential for this result that the lines of force shall be perfectly free at their outer ends; in other words, only a single isolated charge is considered. Now in a structure like the hydrogen atom, composed of a negative and a positive particle, there is bound to be some interference with this freedom of adjustment. In a neutral, non-ionized atom it would appear that all the lines must begin and end within the atomic structure.

J. J. Thomson must be given credit for foreseeing this difficulty, although the Bohr atom was as yet years in the future. He had an atomic concept of his own in mind at that early date, and pointed out that the distance between the particles constituting an atom must be thousands of times the diameter of a particle. "In consequence," said he, "almost all the mass will originate where the lines have their greatest density, near each particle; and the particles are relatively so far from each other that the parts of the lines of force in their immediate neighborhood will have almost perfect freedom of orientation with the motion of the atom."[25]

This is a quantitative question; but it is clear that only under the most favorable conditions will we have a freedom of motion in the atom which approximates that around an isolated charge, and in consequence the electrical explanation of matter, on J. J. Thomson's theory must be approximate in the same degree.

With the neutron, conditions are more rigid. Assuming the neutron to consist of a proton and a negative electron, the union of these must be almost as close as possible; as the neutron, on modern

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23. J. J. Thomson, "Recent Researches in Electricity and Magnetism," p. 21, Oxford, Clarendon Press, 1893.

24. Kaufmann, *Gesell. Wiss. Göttingen*, Nov. 8, 1901; July 26, 1902; March 7, 1903.

25. J. J. Thomson, "Electricity and Matter," N. Y., Scribner's, p. 51, 1904.

theory, may form a constituent of an atomic nucleus. Here we are dealing not with atomic magnitudes but with subatomic dimensions, which is quite another thing. Freedom of motion of the lines of force in such a structure must be almost nonexistent. And, if we make the alternative assumption that the neutron is an independent, non-electrical entity, the electrical theory of matter must admit of an important exception.

But an electrical theory of matter to be acceptable must admit of no exceptions. It must obey the all-or-none principle. If it is approximate in even the slightest degree, we are confronted with the existence of 2 kinds of matter, ordinary and electrical, and we are violating the rule of simplicity in reasoning laid down by Newton.

But has there not been later evidence supporting this theory?

It sometimes has been said that Millikan's oil-drop experiments, by which he measured the charge on a single electron, prove the constancy of this charge, and hence the variability of the mass alone in Kaufmann's experiments. It is true that Millikan found that the charge on an ion *after it had been transferred to the oil-drop* was the same whatever the source of the original charge. Ions of different gases, unquestionably of different speeds, gave the same charge to the drop. But it is to be remembered that the measurement of this charge was made, not at the speed of the ion, but at that of the oil-drop, which was of the order of a few hundredths of a centimeter per second.

The special theory of relativity is sometimes quoted in support of the constant charge and variable mass. It is true that Einstein[26] in his original paper of 1905 gives a formula for the change of mass with the speed of a moving electron, which, like J. J. Thomson's formula, becomes infinite at the speed of light; and that he gives no similar formula for a change in the charge. It will be interesting for us to see how he obtained this result.

In section 10 of his paper Einstein derives the following formula for the x-component acceleration of a moving charged particle, together with formulas for the other components:

$$\frac{d^2x}{dt^2} = \frac{e1}{m\beta^3} X$$

in which e is the charge of the particle, m its rest mass, X the component of the electric vector, and β the familiar $1/\sqrt{1 - v^2/c^2}$.

It is evident that the quantity e/m is altered by the factor $1/\beta^3$, but whether the charge or the mass or both are changed is not obvious. Einstein without comment assumes e to be constant and m to bear the full effect of the modifying factor, and on this basis derives his formula for the change of mass.

This assumption, of course, was orthodox in 1905, but it is of interest to note that as a matter of logic the electrical theory of matter can claim no supporting evidence from the special theory of relativity.

On the basis of this result of Einstein's, Sommerfeld[27] introduced a modification into Bohr's theory of the atom. On Bohr's theory the hydrogen atom was regarded as consisting of a negative electron revolving in a Keplerian ellipse around a positively charged nucleus, the attraction between the 2 charges being balanced by the centrifugal force of the revolving electron. Sommerfeld (page 45) makes the orthodox assumption that the electrical charges remain constant, but that the mass of the revolving electron varies with its speed according to Einstein's formula. In consequence, the mass of the electron fluctuates as it describes its orbit, being greatest at perihelion and least at aphelion, and its centrifugal force will vary slightly from that in a nonrelativistic Keplerian ellipse. Because of this, the orbit becomes an ellipse with a moving perihelion like that of the planet Mercury. The effect of this will be to split the spectral lines, producing what Sommerfeld called the relativistic fine structure.

This predicted effect has actually been found in the spectra of hydrogen and helium, the number of the component lines and their relative separation being in accordance with theory.

As to the value of this result as a confirmation of the electrical theory of matter, it is to be observed that Sommerfeld would have obtained exactly the same modification of the Keplerian ellipse if he had assumed the charge to decrease and the mass to remain constant, thereby disturbing the balance by reducing the centripetal attraction instead of increasing the centrifugal force.

The logic of the whole situation is that the electrical theory of matter can claim no independent support from Millikan, Einstein, or Sommerfeld. It rests for the present on J. J. Thomson's theory, and even this theory assumes tacitly that the charge is unaltered by the motion. It is remarkable that every one we have mentioned, from J. J. Thomson onward, when confronted with the necessity of making a choice, prefers to keep the charge constant and let the mass take the consequences, and this without comment or apology.

Of course, there must be a reason for this; and although it is explicitly stated by no writer whose works I have seen, the reason is doubtless to be found in a fundamental law of electricity, that of the conservation of electrical charge, with its corollary, the exact equivalence of positive and negative electricity. This law states that no one has ever produced the slightest trace of a positive charge without the simultaneous production of an equal and opposite negative charge somewhere in the neighborhood.

This law has been the subject of some very searching experiments. We may operate within a large conducting cube, such as was built by Faraday at the Royal Institution; perform within it all the usual electrical experiments, excite a glass tube by rubbing it with fur, draw sparks from an electrical machine, and yet a sensitive gold leaf electroscope connected to the cube will remain undisturbed. It seems impossible to create or destroy an electric charge without a compensating creation or destruction of an equivalent charge of the opposite sign.

And yet, the era of thought which has not hesitated to question the conservation of energy can

26. Einstein, *Annalen der Physik*, v. 17, p. 891, 1905.

27. Sommerfeld, *Annalen der Physik*, v. 51, p. 1, 1916.

hardly be expected to respect this electrical principle; in fact, this law has been brought under fire from several quarters. If these points of order are sustained they will have an important bearing on future answers to the question "What is electricity?"

It is well to remember in this connection that all the experiments upon which is based the law of conservation of electric charge have started with neutral bodies. The glass tube and the fur were at first neutral, but exhibited equal and opposite charges after being rubbed together; the electrical machine was at first neutral, but on being operated its 2 sides became equally and oppositely charged.

Suppose a chemist should announce that as a result of the analysis of several thousand neutral salts he had come to the conclusion that acid and basic radicals existed in equal amounts in nature; we would likely think him ignorant of such syntheses as that of the acid radical cyanogen (CN) from its elements in the electric arc.

But, is there any known electrical analogue of such a synthesis or its reverse dissociation? No, nothing that we have so far been able to produce in the laboratory; yet if we imagine some race of children of the gods who could play with planets as we with pith balls, something of this kind might come to their notice.

Among the phenomena of atmospheric electricity there is an unsolved mystery. Many fruitless attemps have been made to explain it consistently with the principle of conservation of electrical charge. Continual failure has led more than one physicist to look for the explanation in a slight departure from this principle, and it has been shown that a departure so slight as to be beyond laboratory detection would yet, on the large scale, solve this mystery. The difficulty in question is to account for the negative charge of the earth.

For our earth is not a neutral body. Its entire surface is negatively charged to such an amount that there exists near the surface a potential gradient of 150 volts per meter. The conductivity of the atmosphere is small, but not zero; and because of this conductivity and the potential gradient there is a continual conduction of negative electricity away from the earth amounting, over the whole surface of the earth, to a current of about 1,000 amperes. Small as this may appear, it is sufficient to bring about a loss of 90 per cent of the earth's charge in ten minutes if there were no means of replenishing the loss. The nature of this replenishment is the mystery referred to.

So great has been the difficulty of accounting for this replenishment that in 1916 G. C. Simpson,[28] now director of the British Meteorological Office, raised the question of a possible spontaneous production of a negative charge in the earth's interior, but offered no suggestion as to how this could be brought into line with existing theory.

In 1926 Swann,[29] who had worked unsuccessfully with the same problem, followed Simpson's lead, but chose the other alternative of a slight annihilation, or as he called it, death of positive electricity. He was able to bring this into connection with existing electrical theory by generalizing Maxwell's equations. His fundamental idea was that there might be a very slight difference in the properties and behavior of the 2 electricities. Here again we are reminded of the difference apparently found by Rupp.

Such a suggestion was not without precedent. Lorentz[30] in 1900 had postulated a difference between the attraction of unlike charges and the repulsion of like charges to account for another mystery—gravitation. It must be admitted that the accepted idea of the absolute equivalence and mirror-image character of the 2 electricities had weakened somewhat when such men as the director of the British Meteorological Office, the director of the Bartol Research Foundation, and a Nobel prizeman could join in expressing doubt of its accuracy.[31]

Swann's theory of the maintenance of the earth's charge is, from the theoretical point of view, the most successful that has yet been advanced. He modifies the equations of Maxwell by introducing 2 small terms, amounting respectively to one part in 10^{26} and 5 parts in 10^{19} of the main term of the classical theory. These additional terms involve the acceleration and time rate of change of positive charge.

Swann assumed no similar terms for the negative charge, his idea being that there is a slight differential effect in behavior. For simplicity, therefore, he introduced a differential term applying only to positive electricity. This assumption enabled him to account for a slow death of positive electricity due to the centripetal acceleration produced by the earth's rotation.

To account for the known electrical facts, there is necessary an annihilation of less than one proton per cubic centimeter per day, equivalent to a loss of 0.5 per cent of the earth's mass in 10^{20} years. This would also account for as much of the earth's magnetic field as is symmetrical about the earth's axis, and would give the correct ratio for the magnetic fields of the earth and the sun. Moreover, no development of charge or magnetic field could be detected with a sphere of laboratory size rotating at the highest practicable speed. And finally, Swann's scheme is consistent with the special theory of relativity.

Whatever may be thought of Swann's fundamental assumption, it must be admitted that his theory is experiment-proof. Moreover, even though it should be definitely disproved, it would have the lasting merit of impressing upon us caution in extrapolating laboratory results to the cosmic scale.

The relations of newly discovered fact and existing theory are, as we have seen in this somewhat brief survey, rich in suggestion. Speculation is not dead, but sleeping. If the past is still an indication of the future, it will awake again to renewed activity, and when this occurs we will need a wide acquaintance with fact and a good sense of perspective to guide and direct future speculation on the question, "What is electricity?"

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28. G. C. Simpson, *Monthly Weather Review*, v. 44, p. 121, 1916.

29. Swann, *Journal Franklin Institute*, v. 201, p. 143, 1926; *Phil. Mag.*, v. 3, p. 1088, 1927.

30. Lorentz, Koninklijke Akademie van Wetenschappen te Amsterdam, *Proceedings of the Section of Sciences*, v. 2, p. 559, 1900.

31. Additional references: More, *Phil. Mag.*, v. 21, p. 196, 1911; Gleich, *Annalen der Physik*, v. 83, p. 247, 1927; W. Anderson, *ibid.*, v. 85, p. 404, 1928; A. Press, *Phil. Mag.*, v. 14, p. 758, November 1932.

Modernization of Transmission Lines

The results of a survey by the A.I.E.E. lightning and insulator subcommittee* of the methods used to reduce the effect of lightning on existing transmission lines for medium and high voltages are given in this paper, which summarizes data obtained by means of a questionnaire sent to various operating companies.

INTENSIVE study of the effects of lightning on transmission lines, which has been in progress in the field under operating conditions, in the laboratory, and in theory, has produced during the past 10 years a vast amount of information valuable in protecting lines and equipment. When new lines are constructed, advantage can be taken of the then existing knowledge and theory of lightning effects, but always there are existing transmission facilities which, constructed in the past, do not have incorporated in them the most recent developments in the art of lightning protection.

Recognizing this situation, the committee believed that if it were to collect and present data showing what has been done within recent years, in the light of the better knowledge and understanding of the subject, to improve the lightning performance of existing transmission lines, the information would be of interest and value to engineers. When new ideas and developments in protection appear, they are usually adopted and frequently reported quite promptly. However, in so far as the rebuilding or modernizing of existing lines is concerned, the record of what has been done usually is not made generally available to the industry as promptly as in the case of new development. This is one of the reasons why the committee has undertaken in this paper to make a survey of various methods which have been adopted during the past 10 years or so to combat the influence of lightning on existing transmission lines, and to present, so far as possible, the results of such changes.

A paper prepared by the lightning and insulator subcommittee of the A.I.E.E. committee on power transmission and distribution, recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., January 28–31, 1936. Manuscript submitted Nov. 8, 1935; released for publication Nov. 29, 1935.

The committee wishes to express its appreciation to all companies that have cooperated in supplying data on which this paper is based, and particularly those companies that promptly and in detail sent in information in answer to the questionnaire.

*Personnel of A.I.E.E. lightning and insulator subcommittee: Philip Sporn, *chairman;* I. W. Gross, *secretary;* C. L. Fortescue, H. A. Frey, D. C. Jackson, Jr., W. W. Lewis, J. T. Lusignan, and F. W. Packer.

Scope of the Paper

As already mentioned, this report covers only lines which have been altered in some way to improve their lightning performance, and does not include the protective means which have been used on newly erected lines. The various schemes used are presented and discussed, together with the number of reporting companies using the schemes, system voltages of lines on which changes have been made, and miles of line equipped. Individual schemes are described together with the operating performance (when available) of lines so equipped; and pertinent comments or opinions of the various contributors are given. Also, where details are available, a discussion is given of a few typical examples of construction which have been used.

The operating experience obtained under the various conditions is in most cases rather sketchy, partly because a number of the methods used have been put into effect quite recently, partly because many of the operating records are incomplete, and partly because in some cases only sections of lines have been altered, which leaves the protective value of the scheme used largely up to individual opinion rather than statistical data.

The relative use of the various schemes by different companies and trends in practice are summarized in conclusion.

Method of Obtaining Data

From time to time various companies have reported in detail the means adopted to combat lightning on the various parts of their systems and the operating results obtained. These contributions are distinctly valuable, but, of course, are confined to the methods adopted by some particular company and do not therefore give a broad cross section of what is being done at large. To present a more comprehensive picture of what has been done throughout the country, the committee therefore decided to send to a number of the larger operating companies a questionnaire to obtain data on the various schemes of protection used to improve the performance of existing lines in the voltage classes from 22 kv to 220 kv.

The questionnaire was confined to questions regarding the methods used and results obtained in attempting to better the lightning performance of lines, as it has been shown in the past that troubles from this cause have accounted for as high as 80 per cent of all line outages. Further, the information asked for was confined to rebuilt, revamped, or modernized lines, and did not include new lines which had been constructed with the benefit of the latest knowledge and thoughts on lightning protection. The questionnaire was sent to 15 companies and answers were received from 12. While the companies reporting their experience represent some 20 per cent of the total kilowatt-hour output of the country, it should be pointed out that there are doubtless other companies who have modernized their lines by various methods which may or may not be reported in this paper. Although the data re-

ceived in answer to the questionnaire is not claimed to be inclusive, it is believed to be typical of the practice and experience of a large part of the industry.

In collecting such data it is, of course, impossible to cover all the details of the various types of construction used, but it is believed that the general schemes employed to provide better lightning performance of lines, and the thoughts, as regards the protection expected and afforded, of those engineers who are active in designing and operating these lines, will be of considerable value to a great many who have similar problems to deal with.

Methods Used in Modernizing Lines, and Results

The method of dealing with the effect of lightning on transmission lines has in general been approached from 3 different angles: first, control the lightning when it gets on the line; second, keep the lightning off the line; and third, increase the resistance of the line to flashover from lightning voltages. All these or combinations of them have been used in modernizing lines on which data are reported here. The complete questionnaire which was sent out is too voluminous to give here, but answers to the features outlined therein are presented in summary form in table I and discussed in more detail in the following pages.

Expulsion Protective or Deion Gaps

Of the 12 companies reporting, 9 are using expulsion protective or deion gaps and one other purchased them a year ago for installation on a 44 kv line, but at the time of writing had not yet installed them. As to voltage class, 2 miles of 220 kv line, 206 miles of 132 kv line, 26 miles of 110 kv line, 67 miles of 66 kv line, and 7.5 miles of 26.4 kv line, are equipped with the gaps, with some tubes in use on 13.2 kv lines (this latter voltage is outside the range covered by the questionnaire). In addition to the use of these devices on the lines proper, they have also been installed in a few locations at pole top switches and steel towers on 33 kv lines. Another company reports using them in small quantities to protect cables which form parts of a 22 kv wood pole line, and on lines near station entrances.

The operating record with this method of protection is in most cases rather sketchy. In the 132 kv class, the line operation reported by one company has been very much improved, the average outages for a 7 year period before installation of the gaps being 13 per year, and for 3 years after installation, 5.7 per year. Another line showed 9 yearly outages for a 7 year period before tubes were installed and afterward 4 yearly outages during a 2 year period. On still a third line 11 outages per year occurred during 7 years without tubes, and one outage per year for the 2 year period it was operated with tubes. A 110 kv line showed 8 outages during one year's operation before installation of the tubes, and during one year's operation after, 11 outages. A 69-kv double-circuit steel-tower line, which had a 10 year outage record of 11.3 per hundred miles of line per year, experienced 12 outages on the same basis during the first year equipped with tubes. In this connection, however, the reporting company states: "The majority of tripouts were apparently due to short relay and circuit breaker operating times compared to gap operating time." After the relays had been increased to trip in about 5 or 6 cycles, the record for the subsequent year showed 3 tripouts on one circuit and one tripout involving both lines. These 3 tripouts are included in the 12 just mentioned. This

Table I—General Summary of Answers Submitted by 12 Companies to Questionnaire on Modernization of Transmission Lines

Additional Protection Employed	Number of Companies Using	Kilovolt Rating of Lines	Miles of Line[2] Having Protection: 220 kv	132 kv[6]	110 kv	66 kv	33 kv	22 kv[5]	Effectiveness in Bettering Line Performance: Favorable Comments[3]	Unfavorable Comments
1. Expulsion protective or deion gaps	9	220, 132, 110, 66, 33, 26.4, 13.2	2	206	26	67		7.5	Effective in reducing circuit interruptions	Weathering qualities need improving
2. Additional ground rods	4	140, 132, 66		38		39			Yes—limited data	None
3. Counterpoise wires	6	220, 132, 110, 66	65	28	32	57			Effective in reducing circuit interruptions	None
4. Additional ground wires	8	220, 140, 132, 66, 33	28	172		141	1		Outage ratio of 1 to 4 indicated by one company	None
5. Additional insulators per conductor	5	220, 110, 66, 22	102		37	110		4.5	Beneficial	None
6. Line type arresters	2	66, 25				23			None	Not effective
7. Petersen coils	1	140		250					Effective on line to ground faults	Not effective on most phase to phase faults
8. Wood crossarm braces	4	66, 33, 22				20	128	115	Very effective in reducing line outages	Increased minor splintering of poles and crossarms
9. Insulated guy wires[4]	7	66, 33, 22				20	135	115	Decreased pole and crossarm splitting	Increased pole splintering some guy splitting
10.[1] Grading shields or arcing horns	4	132, 110, 66		287	24	85			Desirable on high voltage lines	None
11.[1] Fused grading shields	2	132, 66				23			None	Large number of replacements — limited experience

1. Information not specifically asked for in questionnaire.
2. Not all companies reported mileage of lines modernized. Only mileage given is recorded.
3. Opinion of company reporting (expressly stated or implied).
4. Alone or in combination with wood crossarm braces.
5. Including 26.4 and 27 kv.
6. Including 140 kv.

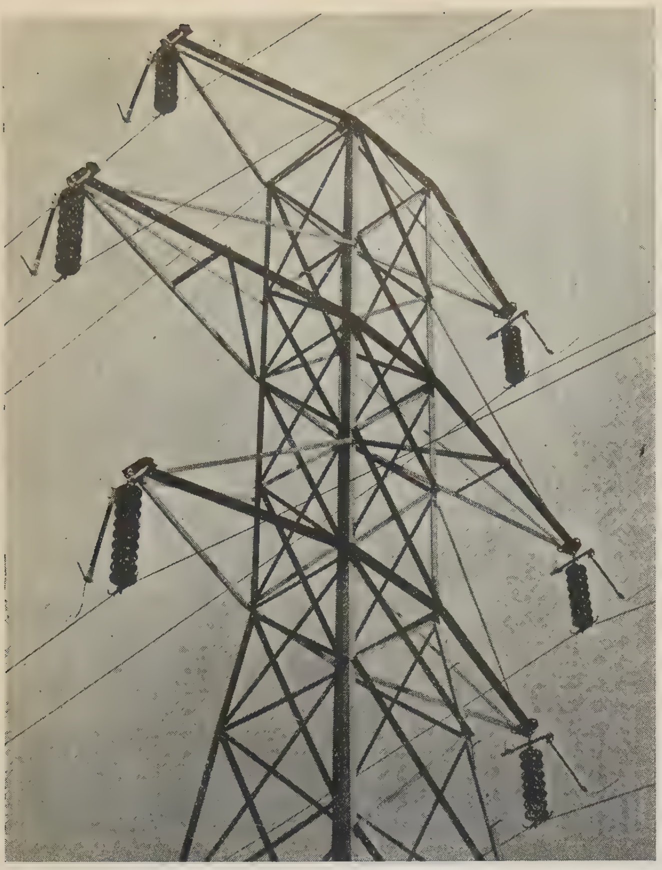

Fig. 1. Expulsion protective gaps mounted on the insulator string at suspension assemblies on both circuits of a 69-kv 2-circuit steel-tower line

company has experienced some difficulty from external flashover of the device.

On a 58-mile 66-kv line equipped with tubes, the outages before installation averaged 12.2 in 4 years' operation, but for the one year's operation with tubes no outages were reported. However, on a 7.5-mile, 26.4-kv line, 7 years of operation before equipping gave an outage record of 2.7 per year, and after installation 6 in one year's operation. No comments were given by the operating company for the lack of protection indicated in the latter.

The general type of construction used in mounting these gaps or tubes has already been covered by various papers, the usual method being either to attach the device on the insulator string or tower structure on high voltage lines, and usually on the supporting structure only in the lower voltage lines, although one company shows the device mounted through an insulator directly on the 24.6 kv circuit. Typical construction methods used by one company on a 2-circuit 69-kv steel tower line are shown in figures 1 and 2, and the construction used on a 66 kv wood pole line by another company in figure 3.

Additional Ground Rods

Four of the 12 companies reported using additional ground rods as a means of reducing tower footing resistance. The mileage definitely reported was 39 miles of 66 kv and 37 miles of 140 kv. One other company reported the use of ground rods at scattered locations on 132 kv lines.

Operating records are not available to indicate the betterment in line performance as the result only of the addition of ground rods. One company, however, reports that on a 140 kv system the troubles per 100 miles of line per year (flashovers) were 17 in a low-resistance 20-mile section of the 38 mile line against 30 cases in the other half of the line which had high tower footing resistance. In the first half the tower footing resistance averaged 52 ohms, and in the second 800 ohms. A 31 mile line (a continuation of this 38 mile line) with modern so-called lightning-proof construction, showed a trouble record of 3 per hundred miles of line per year. This section of the line has an average tower footing resistance of 22 ohms and an average tower footing resistance, where arcover occurred, of 24 ohms. The reporting company draws the following conclusion: "Although the record is very good, it appears that absolute immunity from lightning troubles is almost impossible to obtain."

Counterpoise Wires

Six of the 12 companies reported using counterpoise wires on a total of 182 miles of line in the voltage range from 66 to 220 kv. The various types of counterpoises used are indicated in figure 4. In the 220 kv class, one company reports an average of 5 line outages per year, during a 3 year period before counterpoises were installed, and one per year during a 6 year period after counterpoises were installed. Another company reports 21 outages per year on a 110 kv line during a 6 year period before counterpoises were installed, and 6 per year during a 4 year period after installation of counterpoises. A third company reports no outages on a 220 kv line in one year of operation before counterpoises were installed and 0.6 of an outage per year for the 3 years following with counterpoises in service.

A fourth company installed counterpoises at various sections on the line and has found an apparent decrease in the number of flashovers in these sections in the past 3 years as compared to the previous 5 years, although the use of protective gaps on one circuit does not render the record definite. In this particular case, the use of counterpoises reduced the measured tower footing resistance approximately 50 per cent.

Two companies report cross bonding between towers where 2 tower lines traverse the same right of way. On a 40-mile 2-tower 69-kv line where cross bonding was employed on 224 towers during the past year (1935), 2 outages occurred involving all 4 circuits and one outage occurred involving 2 circuits on one tower line. Three years previous to this time, bonding had been done on 85 towers, and for these 3 years the record showed 17 single circuit outages, 19 double circuit outages, and 1 4 circuit outage.

Scattered cross bonding at 21 towers on a 220 kv line is reported by another company, but obviously the performance record of the line as the result of these changes is hard to evaluate and was not given.

Addition of Ground Wires

Eight of the reporting companies have installed additional ground wires, these being mostly the addition of a ground wire to lines not already so equipped. This practice was adopted on lines for 33 kv, 66 kv, 132 kv, 140 kv, and 220 kv. Approximately 340 miles of line have been modernized in this way, but in most cases other changes were made which make it practically impossible to evaluate the benefits of the additional ground wire alone. Where data are available, a ratio of as high as 4 to 1 between outages before and after the installation of ground wires has been recorded.

Changes in Original Insulation

Five companies report changes to increase line insulation on 22, 66, and 220 kv circuits. A total of 250 miles of line was reported as so treated. In the case of 66 kv lines, the insulation was increased by one company from 5 units to 6, and by another company from 7 units to 8. On the 220 kv line the increase was from 14 units to 16. The amount of increase in the insulation on the 22 kv line was not reported. Reported data indicate decreases in line outages in the order of 8 per cent on 220 kv lines, from 40 to 70 per cent on 66 kv lines, and 20 per cent on 22 kv lines.

On one 30-mile 2-circuit 69-kv tower line the insulation was increased from 7 units to 8 on the top phases, and to 9 on the middle and bottom phases. A ground wire also was added at about the same time. The net effect during a 4 year period before these changes were made as compared with a 3 year period afterward showed approximately the same number of yearly single-circuit outages and a reduction of more than 20 per cent in the yearly double-circuit outages. Later, with the tower line still equipped with one ground wire, the insulation on all 3 phases of one circuit was reduced to 5 units, with the result that during the succeeding 4 years the yearly number of outages on the circuit having 5 units was approximately doubled, although the yearly number of outages on the line retaining the 8 and 9 units was reduced by some 85 per cent. The double-circuit outages were about 70 per cent of the average for the previous 3 years' operation when both lines were insulated with 8 and 9 units. This operating experience checks with the operating results of another company which employed this differential insulation on a 66 kv line, where it was shown that the outages on the underinsulated circuit very much exceeded those on the overinsulated one. In this case, however, comparative results were not possible as the line had never operated with equal insulation on both circuits.

Fig. 2. Expulsion protective gaps attached to the tower arm at dead end assemblies on same tower line as shown in figure 1

Fig. 3. Expulsion protective gap installation on single-circuit 66-kv wood-pole line

Note the horn at the top of the tube to maintain a fixed external gap

Line Type Lightning Arresters

Two companies report the use of arresters on the line proper, one on a 25 kv system, and the other on a 66 kv system. The total line mileage is given as 23 for the 66 kv line, but no record is available on the 25 kv system. In reporting on the performance of line type arresters, the company operating this 66 kv line reported that when first installed no flashovers had occurred at insulator strings equipped with arresters. Following this experimental installation, the line was equipped at each phase of the 2 circuit line about every fourth tower. The company's comment is as follows: "Because the 3 year (1929, 1930, and 1931) tripout record on the circuit equipped with lightning arresters was as bad as its companion circuit not so equipped, and because there were failures of the arresters themselves, the arresters were removed from service at the end of the 1931 season."

Experience in the use of line type arresters is ap-

parently quite limited, and conclusions as to their effectiveness in preventing line outages cannot very well be made because of the limited amount of data available.

Petersen Coils

The use of the Petersen coil has been reported by one company on an extensive (250 mile) 140 kv ungrounded neutral system, in a rather complete report which has been previously published. While the data submitted in answer to the questionnaire include an analysis on the basis of line faults without segregating lightning troubles, a summary record is interesting on the effectiveness of this device in clearing troubles.

For a 5 year period, 70 per cent of all faults were cleared without line interruption. Over 90 per cent of the line-to-ground faults were cleared, and $2^1/_2$ per cent of the short circuits without line interruption. Of faults not definitely classified as to nature (that is, ground faults or short circuits) 70 per cent of the faults were cleared without line interruption.

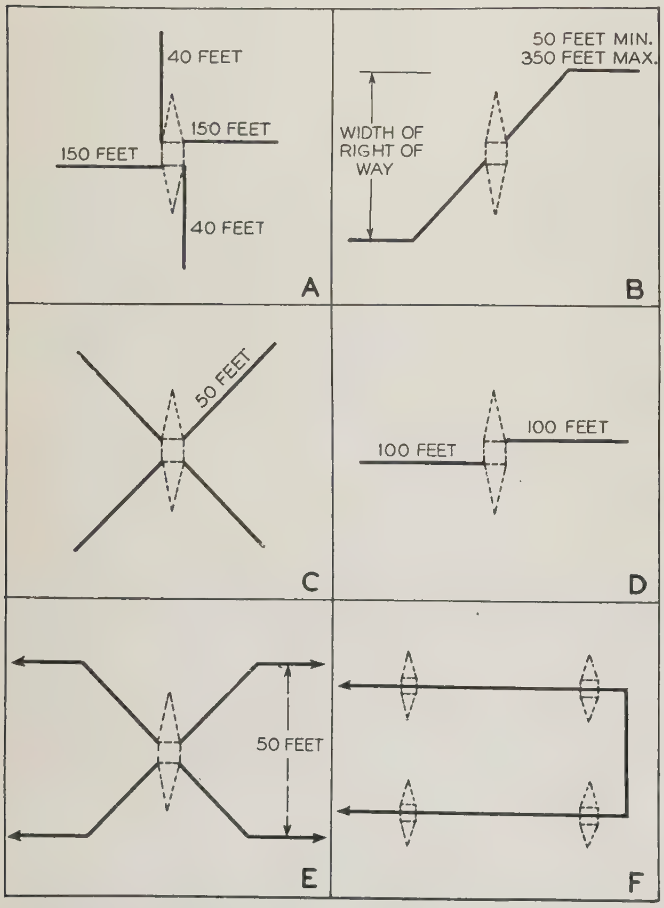

Fig. 4. General types of counterpoises used on lines operating at from 66 to 220 kv

A—Perpendicular crowfoot; galvanized flat strap iron, $^1/_{16}$ by $1^1/_2$ inches
B—Offset parallel; 7 strand "Armco Ingot" iron, $^1/_2$ inch diameter
C—Diagonal crowfoot; 2/0 hard drawn and soft drawn stranded scrap copper
D—Parallel; galvanized flat strap iron, $^1/_{16}$ by 2 inches
E—Double continuous; hot rolled black copper, $^1/_4$ inch diameter
F—Parallel continuous, as used on double tower lines, ended and cross-bonded at roads; 2/0 solid copper

Some single tower lines and single counterpoises using 1/0 copper, also galvanized steel of $^3/_8$ inch diameter. On double tower line construction, one company uses cross bonding without the parallel buried counterpoise wire

All counterpoise wires buried from 12 to 24 inches deep, depending upon local conditions and requirements

Wood Impulse Insulation

Seven companies reported the use of wood to insulate the line more effectively against lightning surges. The types of construction used include substituting wood crossarm braces for metal braces, and insulating the down-lead on poles (on lines either with or without ground wires) to make more effective use of the wood in the existing structure. Where the impulse insulation of the line is increased in this way, guys are usually insulated with wood members, and in some cases porcelain insulators. It appears from the record that the use of wood has been rather extensive in 33 kv lines and also in some 22 and 66 kv voltage classes, and it is also known that it has been used on 110 kv lines (not reported here).

On one 33-kv 2-circuit wood pole line using pin insulators (except at dead end structures) and carrying one ground wire, the steel braces were replaced with wood. The ground wire formerly carried by a steel bayonet at the top of the structure was reinsulated with a wood pole top extension, and the ground lead from the ground wire was offset from the pole, being brought down to a point under the lower conductor, where it was again swung in to the pole and carried to ground. This type of grounding was done at approximately every third pole.

The performance of this line from a 5 year average before changing showed single circuit outages of 3.6 per year and 6.2 double circuit outages. For the 3 years after this reconstruction had been in service, the single circuit outages averaged 2 per year and the double circuit outages 0.3 per year. Views of the field construction actually used are shown in figures 5 and 6. A dead end structure using porcelain and wood guy strain insulators is shown in figure 7.

The same method of procedure was used by one company on a 66 kv line where the pole downlead was offset to take advantage of the pole insulation, but here, on account of the greater physical spacing required by the 66 kv circuit and the suspension insulators used, it was not necessary to use wooden crossarm braces.

Companies reporting on the use of wood on the lower and medium voltage lines have in most cases not given the miles of circuit so equipped which makes the record of total miles of line where rebuilding of this type has been done rather incomplete. However, from the records received, it is interesting to note the extent to which various companies have gone in applying more scientifically the use of wood for impulse insulation. The partial

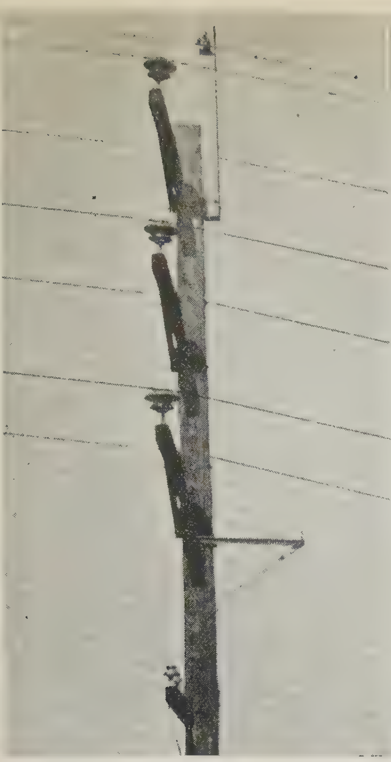

Fig. 5. Wood braces, wood pole top extension, and offset down-lead on 33-kv 2-circuit pin type line. Full advantage has been taken of the impulse insulation of the wood

Fig. 6. Another view of the line shown in figure 5, showing a pole without the down-lead which was used about every third pole

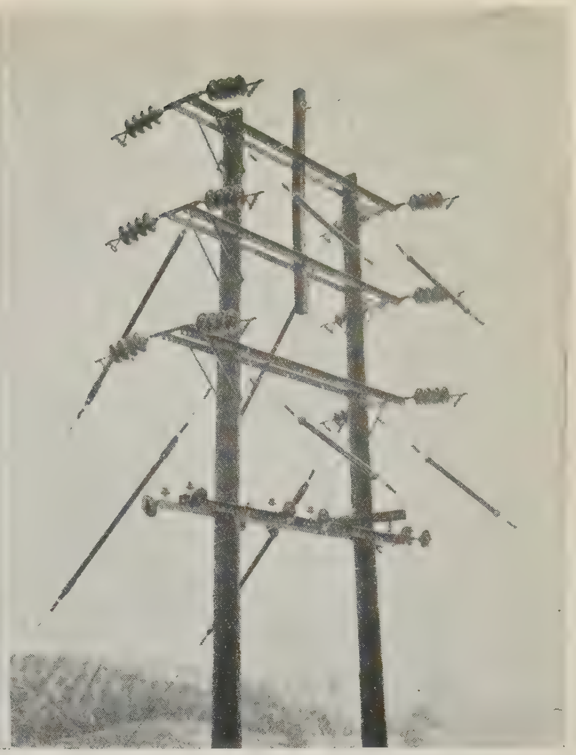

Fig. 7. A 33 kv wood pole line using insulated wooden support for ground wire, porcelain guy insulators (right hand) and wood guy insulators (left hand), also offset pole down-lead

record shows wood used in some form or other (wood arms, wood guys, lowering of guy wires, etc.) on some 270 miles of line, although it is believed the total mileage of lines so equipped is at least double this.

One company reports the use of pole top grounding on a 33 kv system by the use of a pole down-lead extending above the pole top. This pole top protection has apparently been effective in reducing pole splitting previously encountered before these ground leads were extended above the pole top.

Experience of another company in improving the insulation of the line by effective use of wood has shown that without ground wires the pole and crossarm splintering has increased, although it is reported that severe damage to the pole and crossarm, which has been severe enough to require immediate attention, has not been increased.

Another company reports using wood guys on 2 66 kv lines, but not wood crossarm braces. No outage has been experienced in 7 years' operation. Damage to the line has been almost negligible, but about 8 wood strain insulators were very badly shattered and had to be replaced. This company concludes in commenting on the use of wood: "We have less outages, but when we have one the damage is usually quite severe, and the outage is prolonged. Fortunately we have had very few."

A type of construction on a 66 kv line used by one company, similar to that used on the 33 kv line referred to above, is shown in figure 8. Here the steel braces have been retained, but the pole down-lead has been offset, and the ground wire insulated from the pole. A near balance between the impulse insulation of the conductor to down-lead compared to the insulator plus crossarm arcover was obtained without replacing the metal braces.

Another construction used on a single-circuit 33-kv wood-pole pin-type line without ground wire is shown in figure 9. This has been effective in decreasing pole damage (13 per year before to 7 per year afterward).

Other Protective Devices

Several companies report the addition of grading shields, arcing horns, and fused grading rings. Information on these was not specifically asked for in the questionnaire, and therefore any attempt to summarize the use of these devices would probably be misleading in showing the extent to which they have been employed. Four companies report using either arcing rings or grading rings, and 2 companies volunteered the information that they had used fused grading rings. Regarding the grading shields, one company reports that they would not consider building a high voltage line today without installing such protection.

In reference to fused grading rings, one company reports using a few fused grading rings for several years. They have experienced 2 operations of these devices, but express the opinion that they "doubt if this provided any voltage relief from the system." The other company, volunteering information on this

device, installed some 36 on a 66 kv line near the station. They report: "Due to the large number of replacements necessary after each storm, no further use of the fuses was made after 1933 and the rings were removed in 1935 when the 2 overhead ground wires and additional insulators were installed over the whole length of the line." The records are not clear or complete enough to give any indication of the effectiveness of this device in service.

General Summary

Expulsion Protective and Deion Gaps. The gaps, which have been quite extensively applied within the past 2 or 3 years, appear in most instances to be generally effective in reducing line outages initiated by lightning. In most cases, those using them, however, report some doubt as to their weathering qualities and consequent maintenance costs. Some external flashovers of tubes in service have been experienced.

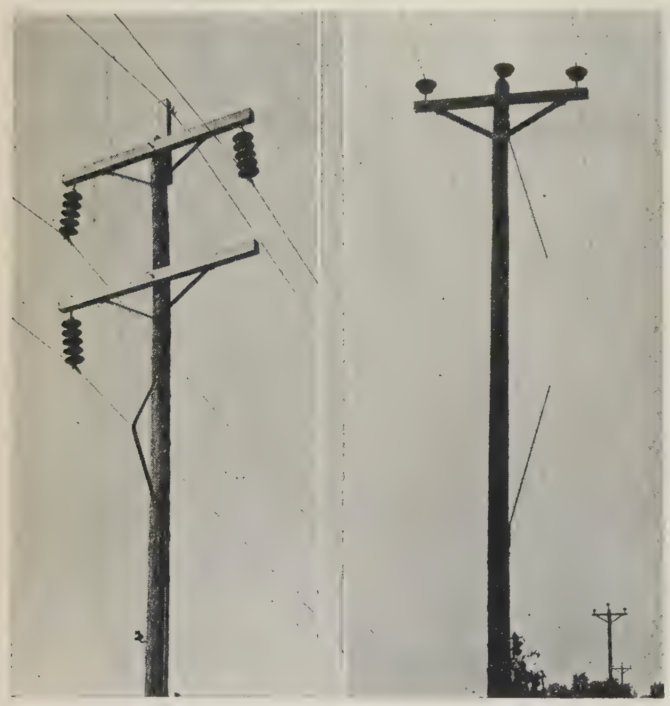

Fig. 8 (left). A 66-kv wood-pole line having pole down-lead insulated (or offset) from pole until after passing bottom conductor

Note wood pole top extension to increase impulse insulation of line

Fig. 9 (right). A 33-kv pin-insulator wood-pole line without ground wire, using wood braces, pole gap, and pole top rod (not visible in picture)

Lightning Arresters. The use of line type lightning arresters for bettering line operation has so far been very limited. The results reported do not at the present time look very encouraging for these devices to have extended use for line protection.

Improvement in Ground Resistance. The attempt to improve line performance by lowering ground resistance has been given considerable attention, particularly in the higher voltage lines of 66 kv and above. Ground rods are used in many cases to decrease the tower footing resistance, but where conditions are such that a reasonable number of ground rods fail to produce the desired low tower footing resistance, the trend is in the direction of installing counterpoises. Considerably more experience will be required before operating data will show conclusively just how much benefit can be attributed to the use of ground rods and counterpoises, although the rather scattered and incomplete records so far available show that this method of controlling lightning on transmission lines is proving effective.

Additional Ground Wires. Additional ground wires have been used to some extent in the higher voltage lines to shield the line wires. Ground wires have not been so extensively used in the lower voltage lines, that is, 33 kv and below. In fact, one company reports having removed them from all of their 25 kv system some years ago. In the high voltage field one or more ground wires seem to be general practice at the present time where a high grade of line performance is desired.

Additional Insulators. While some attempt has been made to insulate lines more highly, the practice has been confined in most cases to those lines which apparently, from present practice and standards, were sub-normally insulated. There does not seem to be any trend, and in fact, no pronounced opinion that the overinsulation of a line is any cure at all for lightning flashover, although it may better the line performance to a limited degree.

Use of Wood for Impulse Insulation. There is a strong trend at the present time among many companies operating wood pole lines to take advantage of the wood insulation to supply impulse strength. Where definite records are available, it appears that considerable benefit has been obtained by the use of wood, line outages being reduced in most cases and no apparent increase of damage to poles, crossarms, insulators, or other equipment reported by any company, although there seems to be a possibility of more severe damage if the wood is not protected (such as by suitable gaps).

Grading Rings and Arcing Shields. The rings and shields are used more for protection against physical damage of the line than for minimizing lightning outages. Where fused grading shields have been used, the reports indicate that they are not in very high favor because of the necessity for replacement after each operation.

Petersen Coils. One company, reporting its experience, believes that the coils have done a very creditable job. These coils appear to be effective principally in clearing system faults which are from phase to ground. Since they operate on ground current only they are not effective in the case of multi-phase faults.

Permanent Magnet Materials

Permanent magnet materials recently have been developed with characteristics radically different from those of previous materials, the carbon, cobalt, and chromium steels. In this paper, the essential properties of these new materials are discussed and are compared with the corresponding properties of the older materials. Development of these new materials has broadened the range of properties from which the designer may choose, and has made available high specific magnetic performance in the low price field.

By
C. S. WILLIAMS
ASSOCIATE A.I.E.E.

Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.

FOR some time following the discovery of cobalt magnet steel little change was evidenced in the field of permanent magnet materials, but during the past few years conditions have been altered by several new developments. The introduction of materials with magnetic and physical properties radically different from those with which engineers were familiar necessitates revision of the viewpoint acquired by long association with the properties available in older permanent magnet materials. It is the purpose of this paper to sift out the facts pertinent to the design and utilization of these new materials, and, without becoming involved in the metallurgical processes necessary to the production of finished magnets, to show the essential properties of the new materials as compared among themselves and with representative materials of the older group. By a comparison of characteristics it is hoped that users of permanent magnets may gain a better perspective of the capabilities and limitations of the materials now available.

Development of these new permanent magnet materials has broadened considerably the range of properties from which the designer may choose, and provides unique properties which were not previously available. With the introduction of these materials, high specific magnetic performance becomes available in the low cost field. Nickel-aluminum-iron alloys and certain combinations of oxides of iron and cobalt provide a new standard of performance in respect to weight. These 2 materials have relatively poor mechanical properties; but with work on them continuing, substantial improvements may be anticipated.

A paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 28–31, 1936. Manuscript submitted Sept. 18, 1935; released for publication Nov. 15, 1935.

1. For all numbered references see list at end of paper.

Four Types of Materials Discussed

Although the list of recently developed materials is a long one, for the purposes of this discussion only those showing most promise of succeeding to practical usage are included. Four materials are placed in this classification: the nickel-aluminum-iron alloys, described by Mishima, Köster, and others;[1–6] cobalt-molybdenum-iron alloys and cobalt-tungsten-iron alloys described by Köster, and by Seljesater and Rogers;[7–12] a nonmetallic material composed of cobalt and iron oxides described by Kato and Takei.[13] A fifth material, a cobalt-nickel-titanium-iron alloy described by Honda,[14] is reported to have interesting properties, but so little detailed information regarding this alloy is available that no discussion of it has been included. Because of conflicting evidence concerning the magnetic properties of these materials, all data used, with the exception of that concerning cobalt-tungsten steel, has been substantiated by work in the Westinghouse laboratories, and it is believed that the figures presented are conservative estimates of the capabilities of the materials.

Determination of the fitness of a material for service in any particular application usually depends upon one or more of the following characteristics: its magnetic properties, its physical properties, its economic status. The elements of this discussion will be segregated into groups corresponding to the items mentioned and will be considered in the same order. It is well to note that the relative importance of these items varies with the conditions surrounding each application and that it is the exceptional case that is decided solely upon the basis of one feature.

Magnetic Characteristics

There is a definite flux density at which each permanent magnet material operates most efficiently. This is the induction at which the "energy product" is maximum, and deviation from this value results in a lowered ratio of output (energy in the external field maintained by the magnet) to volume of material. (The term "energy product" is an expression indicating the product of the corresponding flux density and magnetomotive force at points on the demagnetization curve. This figure can be converted into potential energy external to the magnet material, by dividing by 8 π. The resulting quotient is in terms of ergs per cubic centimeter of magnet material.) Correlated with the flux density at which the energy product is maximum is the magnetomotive force against which the magnet can maintain this flux density, and the service conditions required to cause both the operating flux density and the magnetomotive force to correspond to the optimum values must be met if the material is to be

utilized most efficiently. The higher the values of operating induction and magnetomotive force, the greater the energy capabilities and the smaller the volume of material required for a given duty. The values of operating inductions and magnetomotive forces usually may be inferred from the residual induction (B_r) and the coercive force (H_c), respectively. These latter terms are the commonly designated properties of a permanent magnet material.

Among the older materials the highest coercive force was exhibited by 35 per cent cobalt steel with a value of 250 oersteds. The residual induction values extended from about 8,500 to 11,000 gausses, the latter being found in tungsten steel. With the introduction of the new materials, previous maxima were exceeded and materials now are available with coercive forces of 1,100 oersteds and others with residual inductions up to 13,500 gausses. A listing of the approximate ranges found in the new materials follows:

Material	Range of Alloying Elements	Coercive Force, Oersteds	Residual Induction, Gausses
Oxide		300–1,100	6,000– 1,500
Ni-Al-Fe	15–30% Ni, 8–15% Al	100– 600	8,000– 4,000
Co-Mo-Fe	2–12% Co, 10–19% Mo	30– 300	12,000– 8,000
Co-W-Fe	15–30% Co, 15–20% W	30– 150	13,500–11,000

Ni = nickel; Al = aluminum; Fe = iron; Co = cobalt; Mo = molybdenum; W = tungsten.

Figures for the composition of the oxide magnet material were omitted from the preceding tabulation, because of the uncertainty of the actual values. It is probable that the components of the material in its final form differ from those used as the base of the material in relative proportions or even in actual composition. Oxygen variations can occur during heat treatment, either as addition or removal of oxygen from the body or as the transformation of one oxide form into another. The inventors have published a composition of approximately 16 per cent cobalt oxide (CoO), 34 per cent ferric oxide (Fe_2O_3), and 50 per cent ferroso ferric oxide (Fe_3O_4). It is of advantage from the cost standpoint to keep the cobalt content low, but materials of good magnetic properties are made more easily with somewhat higher cobalt contents.

The wide ranges of coercive forces and residual inductions listed for each material are the results of modifications of composition and variations in heat treatment. It is generally true that in the range of properties available in a given material, the extreme values of coercive force or residual induction are accompanied by such a value of the complementary property as to result in a decreased energy product. Thus for each material there is some intermediate combination of properties that gives the maximum energy product. It is interesting to note that despite the variety evidenced in coercive forces and in residual inductions, the energy products of the oxide, nickel-aluminum, and cobalt-molybdenum materials are all of the same order of magnitude as that of

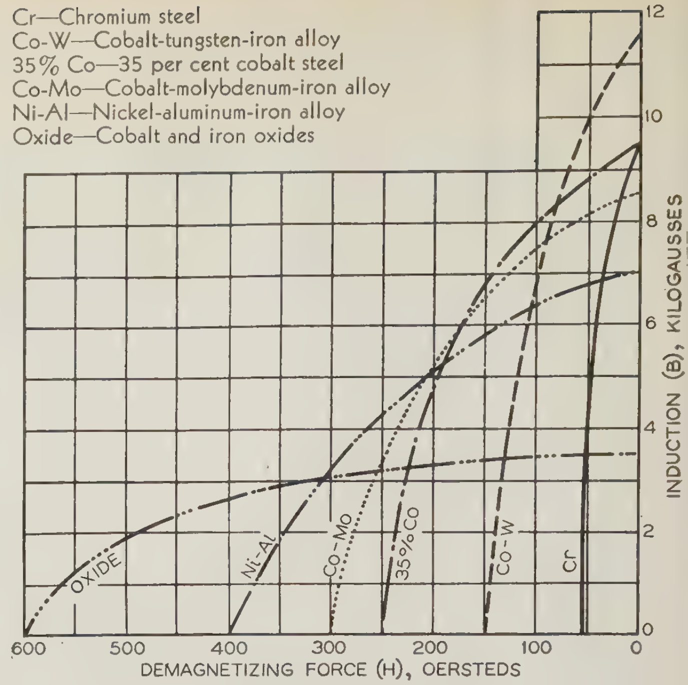

Fig. 1. Demagnetization curves for permanent magnet materials

Intersections of the curves with the abscissa indicate the coercive forces (H_c); with the ordinate, the residual inductions (B_r)

35 per cent cobalt steel. The magnetic properties of these intermediate materials together with those of 2 of the older ones, chromium steel and 35 per cent cobalt steel, are shown in figure 1 by the demagnetizing portions of their hysteresis loops.

For the oxide and nickel-aluminum materials the limit of coercive force extends far beyond the 250 oersteds found for cobalt steel. The coercive force is an indicator of the magnetomotive force against which a given magnet can operate; hence this property is of great importance where magnetic structures include large air gaps or where the magnet may be subjected to large demagnetizing forces in service. It should be noted that the high values of coercive force are gained at the expense of the residual induction, the effect being to reduce the optimum operating flux density and thus increase the necessary cross sectional area of the magnet. In the cobalt-tungsten alloy, coercive force has been sacrificed to achieve high residual induction and correspondingly high operating flux density.

Because of the manner in which the magnetic properties are developed in the nickel-aluminum, cobalt-molybdenum, and cobalt-tungsten alloys, they suffer but little when subjected to high temperatures. This is a result of the relatively great constitutional stability of these materials when at or near room temperature. This is in contrast with the older carbon steels in which constitutional changes continue over long periods of time, unless they are hastened by an increase in temperature for a short interval. Such artificial aging usually causes substantial decreases in the magnetic potency of materials so treated.

The new and different magnetic properties of the

special alloys may introduce some difficulties in application, inasmuch as design or the geometry of magnets varies in accordance with the magnetic properties. Thus new and different properties require new and different designs. The change in design is necessary because of the fact that the higher the magnetomotive force at which the material is capable of operating, the less the length of magnet required for a given duty. Likewise the lower the operating flux density, the greater the required cross sectional area of magnet.

Figure 2 shows the relative lengths of magnets made of these materials when each magnet is to maintain the same external field. Figure 3 shows the cross sectional area of these same magnets. The lengths of magnet required for the oxide, nickel-aluminum, and cobalt-molybdenum materials are all less than for any of the older ones. This difference is especially pronounced when the new materials are compared with the 2 per cent chromium steel now so generally used. However, particularly for the oxide and the nickel-aluminum materials, the required cross sectional areas are much greater than for materials with lower coercive forces.

These magnetic peculiarities must be kept in mind when designing the magnetic structures, else the magnet may be found to be working at a lowered efficiency or perhaps failing its purpose entirely. In general it is not permissible to substitute the new materials, shape for shape, for old ones in existing structures. There is one exception, in that the cobalt-molybdenum-iron alloy may have characteristics sufficiently similar to those of cobalt steel to permit these 2 materials to be used interchangeably in a given design with substantially equal efficiency. The old conception of the desirable shape for a magnet, usually an elongated horseshoe, must be revised when contemplating the use of these new high coercivity materials. Instead of the elongated type of structure and the elaborately curved shapes which frequently were necessary to provide the needed length of magnet, the new structures are likely to be short bars—sometimes so short that the effective diameter is greater than the length. When cobalt steel was the only available high performance material, its high cost as compared with the other materials limited its use and thus made of it a special material. This made its use more carefully planned. Now that the cost barrier to high performance material has been lowered (by these new materials, as will be discussed later) the widened field of use may bring tendencies toward less careful designing which would not be conducive to the proper displaying of the good qualities of the materials.

To digress somewhat, it may be appropriate to mention a condition often found in the testing of magnets to determine their suitability for commercial applications. Instances have been observed where the acceptance test for a magnet had little semblance of the actual working conditions. It is important that the test duplicate the working conditions as closely as possible. For example, if a magnet is to be used in a magnetic circuit that includes an air gap, this air gap or its equivalent should be included in the test circuit; otherwise the test may give misleading data. The strict adherence to an arbitrary test not properly related to working conditions may result in magnets designed not for best performance in service, but solely to meet the test—thus providing maximum performance under the test conditions, but condemning them to operation at considerably lowered efficiency during their useful lives.

Physical Characteristics

The cobalt-molybdenum and cobalt-tungsten alloys can be machined and forged with no more difficulty than the tungsten and chromium magnet steels now in common use.

Both the nickel-aluminum and the oxide materials have limitations imposed by their physical properties and by the procedures necessary to their fabrication. Contrary to the usual in permanent magnet materials, the nickel-aluminum alloy has a coarse structure. It possesses no great mechanical strength, and it is very brittle. Neither forging nor machining is possible with the types of alloy now available. This limits shaping methods to casting and grinding.

The mechanical strength of the oxide material is lower than that of the nickel-aluminum alloy. It is made up of sintered compressed powders, and since the sintering is not carried to completion the finished material is mechanically weak; in fact, it might be termed fragile. This is especially true of the extremely high coercivity materials, as the sintering

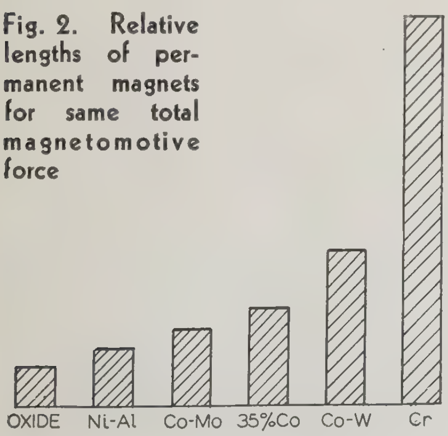

Fig. 2. Relative lengths of permanent magnets for same total magnetomotive force

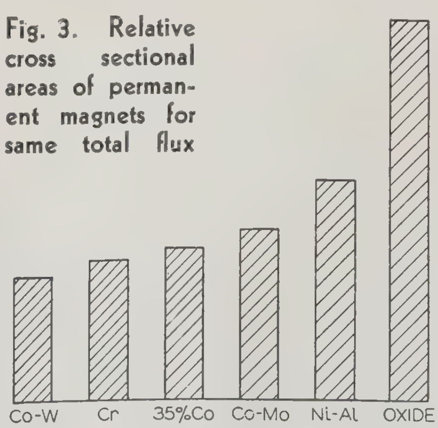

Fig. 3. Relative cross sectional areas of permanent magnets for same total flux

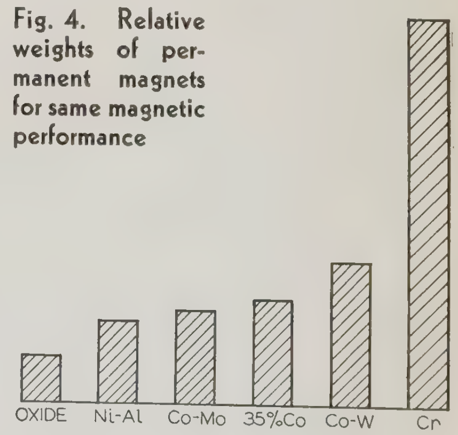

Fig. 4. Relative weights of permanent magnets for same magnetic performance

For explanation of symbols see subcaption of figure 1

is less advanced in these than in those of lower coercivity. It is necessary to provide some protection, such as a film of metal sprayed or plated on the surfaces. The powdered material is molded cold before the final sinter, and in this condition it can be carved into shapes for which no molds are available, but this is a delicate operation. Simple operations such as drilling may be carried out after the final sinter, if done with care. Magnetizing is accomplished best at high temperatures. A temperature of 300 degrees centigrade is given by the inventors as one satisfactory for this process, but temperatures somewhat higher than this are not harmful. The orientation and location of the magnetic path through the magnet and the location of the poles on the surface are fixed during this treatment; therefore, specially devised methods for applying the magnetic field may have to be employed if the shape of the magnet is not simple.

In some applications reduction of weight is a factor of major importance; for these the nickel-aluminum alloy and the oxide material possess properties of interest. Both the nickel-aluminum alloy and the oxide material combine large energy products with specific gravities that are lower than usual, both features tending to produce a high output from a small weight of material. The oxide material has a specific gravity but slightly greater than half that of cobalt steel; and since their energy capabilities on a volume basis are about equal, the oxide material has a phenomenally low weight for a given duty. The relations of the weights of materials required for the same magnetic performance are shown in figure 4. The oxide magnet has considerably less weight than the nickel-aluminum magnet and but $^1/_8$ that of chromium steel. The nickel-aluminum alloy has a specific gravity about $^9/_{10}$ that of cobalt steel; hence it possesses a slight weight advantage over cobalt steel and a decided advantage over chromium steel.

A feature unique to the oxide material is its high electrical resistivity. Whereas all other practical permanent magnet materials have electrical resistivities expressed in microhms per centimeter cube, the resistivity of the oxide material, while varying with treatment, is of the order of thousands of ohms per centimeter cube.

Economic Status

However desirable the magnetic properties of a material may be, its economic status is an important factor in determining the extent to which it will be used. In determining relative desirability (from an economic standpoint) the criterion is the amount received for the amount expended; and since this discussion deals in terms of magnetic energy, neither the cost per unit of weight nor the cost per unit of volume is used, but the cost per unit of magnetic performance, that is, the cost per unit of energy the material is capable of maintaining in its external field. This method of comparison as it is used herein does not take into consideration the relative sizes, shapes, or weights of the materials involved, but shows only the relative costs of materials for magnets made of the different materials, each magnet being capable of doing the same work. As an example of the way in which this system of computation may function, one material may show such magnetic excellence as to require but half the weight of another material in performing the same service; but if the cost per pound of the first be twice that of the second, the cost per unit of magnetic performance would be identical.

The relative costs of materials per unit of magnetic performance are shown in figure 5. When comparing cobalt steel with chromium steel it is found that although the energy product of the former is approximately 4 times that of the latter, the cost per pound is about 6 times as much; hence the cost per unit of magnetic performance of the chromium steel is but $^2/_3$ that of the cobalt steel. In comparing the nickel-aluminum alloy with chromium steel, it is found that although the energy product of the nickel-aluminum alloy is 4 times that of chromium steel, the cost per pound is only double, making the cost per unit of magnetic performance of the nickel-aluminum alloy but half that of chromium steel. Thus there is a radical change in the economic picture. Prior to the introduction of these new materials the only material available for service where space or weight considerations were of importance was an expensive one, while now there are several materials of comparatively low cost ready to be utilized.

It should be noted that the foregoing cost relationships apply only to the cost of material involved, that is, they do not include costs of fabricating, treating, etc. A comparison of the costs of finished magnets is difficult to make because of the entry of fabrication cost factors. The number of pieces to be made, complexity of form, and the amount and kind of machining to be done, all have an important bearing. Also a general comparison cannot be made because the use of the nickel-aluminum alloy and the oxide material would not be considered under certain circumstances. Suffice it to say that for simple shapes which can be readily cast or molded, and where little machining and little mechanical strength are required, the cost of finished magnets should remain in the same order as in figure 5, but with less difference between the relative costs of magnets

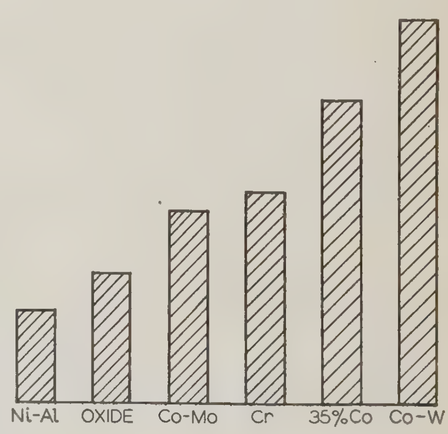

Fig. 5. Relative costs of materials of permanent magnets for same magnetic performance

made of the various materials than between the costs of materials only. Where these conditions are met and the number of units to be made is large, the cost ratio might assume the following order and value: With the cost of nickel-aluminum alloy magnets taken as 1.0, the relative cost of oxide magnets is estimated at 1.2; of chromium steel and cobalt-molybdenum alloy magnets at 1.5; cobalt steel magnets 2; and cobalt-tungsten alloy magnets 2.5. It should be realized that these figures apply to only one set of conditions and as such are not generally applicable.

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The Compensated Thermocouple Ammeter

By
W. N. GOODWIN, R.
FELLOW A.I.E.E.
Weston Electrical Instrument Corp., Newark, N. J.

Temperature distribution and heat flow in electrical conductors have been subjected to a mathematical analysis, which brings out a number of interesting thermal characteristics of conductors. The material presented in this paper is divided into 2 principal parts, the first being a general solution of the problem of determining temperature and heat distribution in conductors, and the second containing the development of the theory of the electrothermic ammeter of the thermocouple type, together with its compensation features. Practical applications of the theory are presented.

In the year 1906, during an investigation of the thermal relations in instrument shunts, an analysis was made of the heat flow and temperature distribution in the conductors, which led not only to improvements in shunt design, but also to the development of a novel form of electrothermic ammeter,[1] and to extensions of the theory with further interesting applications. It has been suggested that this analysis would be of general interest, and for this reason it is published despite the lapse of time.

In the investigation described in this paper it is assumed that the ends of a conductor of uniform cross section are connected to terminals to absorb the heat conducted to them from the conductor heated by a current passing through it, or by other means, such as radiant energy incident upon or emitted by it, uniformly distributed. The problem is to determine the steady state temperature at any part of the conductor, and other thermal characteristics as applied to shunts and thermal instruments, and to develop the theory of the thermocouple ammeter and its compensation feature. The material contained in this paper may be summarized briefly as follows.

The theory of the electrothermic ammeter of the thermocouple type and of the means for compensating it for undesirable temperature effects are described.

As a measure of current, use is made of the difference in temperature between a point on the heating conductor and its terminals, produced by the flow of heat to the terminals through the conductor against its thermal resistance, which is analogous to measuring current by the difference of potential produced in a shunt by the flow of current through it against its electrical resistance.

A paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 28–31, 1936. Manuscript submitted Oct. 28, 1935; released for publication Nov. 22, 1935.

1. For all numbered references see list at end of paper.

To compensate for effects of unequal terminal temperatures and variations in air temperature the cold ends of the couple are connected to the centers of compensating conductors thermally equivalent to the heating conductor, which are thermally connected at their ends to both terminals.

To prove this: assume a conductor of length L, of uniform cross sectional area a, having a thermal conductivity k, and electrical resistivity ρ, connected between heat absorbing terminals at temperatures T_1 and T_2 above surrounding medium, heated uniformly by an electric current or other means, at a rate of w watts per centimeter length as in a shunt, thermal ammeter, or other thermal instrument or device, cooled by conduction to the terminals and by convection at the rate of c watts per centimeter length per degree temperature elevation above the cooling medium. Then the difference in temperature between the center of the conductor and the mean of the terminal temperatures is given by equation 8 of this paper, namely:

$$\left[t_c - \frac{T_1 + T_2}{2}\right] = \frac{v^2}{8k\rho}\left[\frac{2\left(1 - \dfrac{1}{\cosh \dfrac{Ln}{2}}\right)}{\left(\dfrac{Ln}{2}\right)^2}\right] - \frac{T_1 + T_2}{2}\left(1 - \frac{1}{\cosh \dfrac{Ln}{2}}\right)$$

where $n = (c/ak)^{1/2}$. Ln may be considered as the angle in hyperbolic radians, subtended by the conductor. (See appendix I for list of symbols.)

When convection is zero, which is approximately the case in a thermally very short conductor, i. e., where Ln is small, this reduces to the simple relation $t_c - (T_1 + T_2)/2 = v^2/8k\rho$, where v is the voltage drop across the conductor.

In the compensated instrument, the compensating conductor may be considered as a special case of the general equation given above by making v zero, by means of which the terms of the general equation containing terminal temperatures are eliminated, making the difference in temperature between the centers of the heating and compensating conductors, and consequently the indications, independent of variations in ambient and terminal temperature for any thermal length of the conductors.

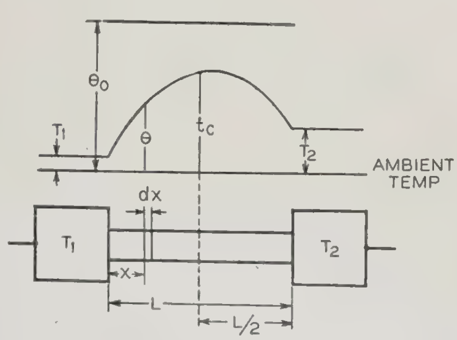


Fig. 1. Temperature distribution in a conductor between terminals, heated uniformly by current or otherwise, cooled by convection and by conduction to terminals

Equations are developed for determining temperature and heat distribution in a plurality of different conductors in series; for determining the rate of heat transferred to the terminals; for computing the effect upon conductor temperature as the result of heat lost through attached thermocouples, particularly in thermocrosses, etc. Practical applications are given of the use of the equations to shunts, etc., and curves are plotted showing temperature and heat distribution for conductors subtending various hyperbolic angles, to facilitate computation.

General Solution

The most general problem under the assumed conditions is where the heat generated in the conductor is dissipated both by surface loss to the surrounding air or other cooling medium, and by conduction lengthwise through its cross section to the terminals. This surface loss will be referred to in this paper as convection, for simplicity, although part is the result of radiation, which is relatively small under the conditions.

Newton's law of cooling is assumed; that is, the rate of heat transfer by convection or the emissivity, is proportional to the difference in temperature between the heated object and surrounding air. This is not strictly correct as it has been found experimentally to be more nearly proportional to the $^5/_4$ power of this difference, but it is a sufficiently close approximation for the temperature differences used in measuring instruments.

Figure 1 illustrates a uniform conductor of length L connected between terminals. The curve above the conductor shows the temperature distribution along the conductor and terminals. In this diagram and in the analysis which follows:

c = heat dissipated by convection per degree elevation in temperature above the cooling medium per unit time in unit length of conductor.
k = thermal conductivity of conductor.
a = area of cross section of conductor.
w = the rate at which heat is generated per unit length of conductor. This will be positive for generated heat or that absorbed by radiation, and negative for heat emitted by radiation.

The positive direction for heat transfer is in the direction of increasing values of x.

T_1 and T_2 = the temperature elevations above the surrounding air of the 2 terminals, respectively.

Then at any distance x from terminal T_1, the heat generated in dx per unit time is wdx, and the heat dissipated by convection is $c\theta dx$ per unit time.

Therefore, the net heat rate available for transfer across dx is $(w - c\theta)dx$.

Now, the rate at which heat conducted through the conductor at x per unit time varies across dx is

$$ak\left(\frac{d^2\theta}{dx^2}\right) dx.$$

Equating these,

$$ak\left(\frac{d^2\theta}{dx^2}\right) = -(w - c\theta) \tag{1}$$

The sign is negative for the reason that the direction of heat flow relative to the positive direction of

x at any point has a sign which is always opposite that of the gradient at that point.

Multiplying both sides of this equation by $2\frac{d\theta}{dx}dx$ and integrating,

$$\left(\frac{d\theta}{dx}\right)^2 = \frac{c\theta^2}{ak} - \frac{2w\theta}{ak} + A_0 \qquad (2)$$

To simplify, let

$c/ak = n^2$ and $w/c = \theta_0$

therefore,

$w/ak = c/ak \times w/c = n^2\theta_0$

These values have a very useful physical significance which is apparent from their defining equations. n is the reciprocal of that length of the conductor which will dissipate as much heat by convection per degree of uniform temperature elevation above air, as it will conduct lengthwise through its cross section by a temperature drop of one degree uniformly distributed over this length; θ_0 is the temperature elevation above the cooling medium which the conductor would have if all the heat generated were dissipated by convection, that is, if none were conducted away.

Substituting these values in equation 2 and after adding and subtracting θ_0^2; substituting A^2 for the constant $\left(\theta_0^2 - \frac{A_0}{n^2}\right)$; and reducing,

$$dx = \frac{d\theta}{nA\left[\left(\frac{\theta_0 - \theta}{A}\right)^2 - 1\right]^{1/2}} \qquad (3)$$

Integrating equation 3, there results, after reducing,

$$\frac{\theta_0 - \theta}{A} = -\cosh (x + B)n \qquad (4)$$

where A and B are constants of integration.

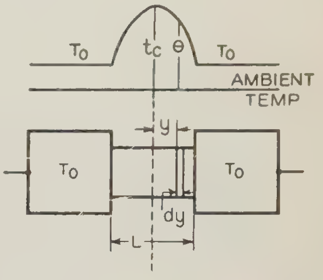
The constants A and B are determined from the known conditions that when $x = 0$, $\theta = T_1$, and when $x = L$, $\theta = T_2$. Expanding $\cosh (x + B)n$; applying the boundary conditions; and reducing:

$$\theta = \theta_0 - \left[\frac{(\theta_0 - T_1)\sinh (L - x)n + (\theta_0 - T_2)\sinh xn}{\sinh Ln}\right] \qquad (5)$$

This is the general equation which gives the temperature at any point along a uniform conductor subject both to convection from or to its surface, and conduction through the conductor to or from the terminals, when heat is uniformly added to it or removed from it. It can be applied to the analysis, among others, of the following practical problems: (1) when heat is generated in the conductor by an electric current, as in a shunt or thermocouple ammeter; (2) when heat is produced in the conductor by radiant energy from a higher temperature radiator, as in a radiation meter used to measure radiant flux; in both these cases θ_0 is positive; (3) when the heat is radiated from the conductor to a cooler medium, as in a radiation meter, itself radiating energy into space, in which θ_0 is negative; and (4) where no heat is added to or taken from it, except that which takes place by convection, and by conduction to or from the terminals; in all of which cases $\theta_0 = 0$.

The quantity Ln, that is, $L\,(c/ak)^{1/2} = L/\left(\frac{ak}{c}\right)^{1/2} = L/L_0$, is a hyperbolic angle and represents the ratio of the actual length L of the conductor to that length which might be termed the unit of thermal length of the conductor L_0, the physical significance of which was given earlier in the paper. If $L = L_0$,

Fig. 2. Temperature distribution in a conductor between terminals, heated uniformly by current or otherwise, and cooled only by conduction to terminals



then L may be said to subtend a hyperbolic angle of one hyperbolic radian. (For similar use of hyperbolic angles in electric circuit problems, see reference 2.)

Special Cases

In many practical cases, the temperature at the center of the conductor is the one most useful to know.

This is obtained by making $x = L/2$ in equation 5, or

$$t_c = \theta_0 - (\theta_0 - T_1 + \theta_0 - T_2)\left[\frac{\sinh \frac{Ln}{2}}{\sinh Ln}\right]$$

$$= \theta_0 - \left(\theta_0 - \frac{T_1 + T_2}{2}\right)\left[\frac{1}{\cosh \frac{Ln}{2}}\right] \qquad (6)$$

Subtracting $\frac{T_1 + T_2}{2}$ from both sides of equation 6 and rearranging,

$$\left[t_c - \frac{T_1 + T_2}{2}\right] = \left[\theta_0 - \left(\frac{T_1 + T_2}{2}\right)\right]\left(1 - \frac{1}{\cosh \frac{Ln}{2}}\right) \qquad (7)$$

This shows that the temperature at the center of a conductor connected to terminals of unequal temperature is the same as if the terminal temperatures were both equal to the mean of their temperatures.

Conductor Heated by Current

Equation 7 can be put into more convenient form for this case by substituting for θ_0 its value in terms of the electrical constants of the conductor as follows:

By definition, $\theta_0 = w/c$. Substituting for w, the watts generated per centimeter length, its value in

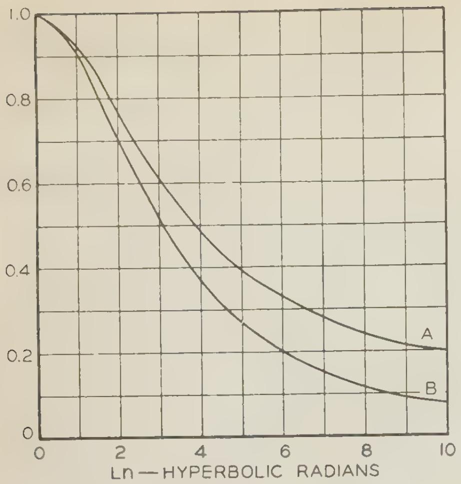


Fig. 3. Heat and temperature ratios determined by the analysis

Curve *A*—Ratio of the heat conducted to the terminals from a conductor, uniformly heated, to the total heat generated

Curve *B*—Ratio of the temperature above air of the center of a conductor cooled both by convection and conduction, to that which it would have if all heat were dissipated by conduction to the terminals

$$A = \frac{\tanh \frac{Ln}{2}}{\frac{Ln}{2}} \qquad B = \frac{2\left(1 - \frac{1}{\cosh \frac{Ln}{2}}\right)}{\left(\frac{Ln}{2}\right)^2}$$

terms of the voltage drop over the conductor v; its length L; and its resistance $L\rho/a$, where ρ is the resistivity of the material; and for c its value n^2ak as defined, there results

$$\theta_0 = \frac{w}{c} = \frac{v^2}{k\rho}\left(\frac{1}{L^2n^2}\right)$$

which when substituted in equation 7 gives

$$\left(t_c - \frac{T_1 + T_2}{2}\right) = \frac{v^2}{8k\rho}\left[\frac{2\left(1 - \frac{1}{\cosh \frac{Ln}{2}}\right)}{\left(\frac{Ln}{2}\right)^2}\right] - \frac{T_1 + T_2}{2}\left(1 - \frac{1}{\cosh \frac{Ln}{2}}\right) \tag{8}$$

Thermally Short Conductor

When the conductor is relatively so short or of so large a cross section that the heat dissipated by convection is negligible in comparison to that conducted away to the terminals, or if the convection factor c can be made negligible, then the temperature relations along the conductor can be determined from the general equation 5 by making $c = 0$, which makes $n = 0$.

Rearranging equation 5, substituting for θ_0 its value w/akn^2, and letting y represent $(L - x)$ for simplicity,

$$\theta = \frac{w}{ak}\left[\frac{\sinh Ln - \sinh yn - \sinh xn}{n^2 \sinh Ln}\right] + \left[\frac{T_1 \sinh yn + T_2 \sinh xn}{\sinh Ln}\right]$$

When $n = 0$, this reduces to an indeterminate form, to evaluate which, differentiate numerator and denominator with respect to n. This result also reduces to an indeterminate form and to evaluate it completely, it is necessary to make 2 additional differentiations, and after simplifying and replacing y by its value $(L - x)$, it reduces to

$$\theta\Big]_{n=0} = \frac{w}{ak}\left[\frac{x(L - x)}{2}\right] + \left[\frac{T_1(L - x) + T_2 x}{L}\right] \tag{9}$$

which is the temperature at any point along a conductor through which all heat is conducted and none lost from its surface to the surrounding medium.

Temperature at Center of Conductor, for No Surface Loss

This is found by making $x = L/2$ in equation 9 or

$$t_c = \left(\frac{w}{ak} \times \frac{L^2}{8}\right) + \left(\frac{T_1 + T_2}{2}\right)$$

Substituting for w its value, $\frac{v^2a}{L^2\rho}$, then

$$\left(t_c - \frac{T_1 + T_2}{2}\right) = \frac{v^2}{8k\rho} \tag{10}$$

which shows that for a thermally short conductor the difference in temperature between the center of the conductor and the mean of the terminal temperature, or either terminal if at equal temperatures, depends for any given material of constant thermal and electrical conductivities only on the voltage drop over the conductor, and is otherwise independent of its length. The nature of the material enters simply as the ratio of its electrical to thermal resistivities.

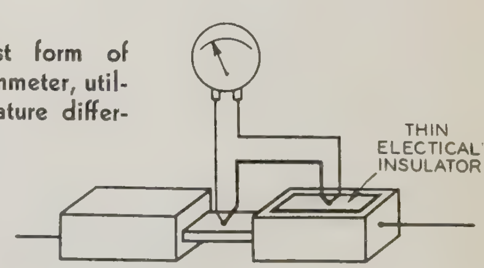
A very practical case is that in which the 2 terminals have the same temperature T_0 which when substituted in equation 9 gives

$$(t_c - T_0) = \frac{v^2}{8k\rho} \tag{11}$$

This equation can be deduced directly very simply by taking the center of the conductor as the origin of co-ordinates as shown in figure 2 where by symmetry the temperature t_c is a maximum and the temperature gradient $d\theta/dy = 0$, and after a single integration and applying the boundary condition, there results:

$$(t_c - \theta) = \frac{wy^2}{2ak} \tag{12}$$

Fig. 4. Simplest form of thermocouple ammeter, utilizing the temperature difference between a point on a thermally short heating conductor and a terminal



which shows that the distribution of temperature along a conductor having no convection losses is parabolic.

This reduces, for the center of the conductor and for terminal temperatures T_0, to

$$(t_c - T_0) = \frac{wL^2}{8ak} = \frac{v^2}{8k\rho}$$

which is the same as equation 11.

Effect Produced by Convection Losses

Upon comparing equations 8 and 10, it will be observed that if the average temperature of the terminals is equal to the air temperature, that is, if $T_1 + T_2 = 0$, then the temperature elevation of the center of a conductor, subject to both conduction and convection, can be obtained by multiplying the corresponding temperature, which the conductor would have if convection were negligible, by the factor

$$\frac{2\left(1 - \dfrac{1}{\cosh \dfrac{Ln}{2}}\right)}{\left(\dfrac{Ln}{2}\right)^2}$$

This factor is shown plotted for various values of Ln in the curve in figure 3.

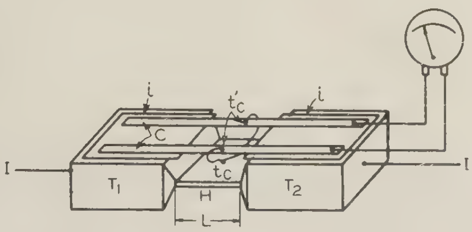


Fig. 5. Method of compensating a thermocouple ammeter for variations in terminal and ambient temperatures

Heat Conducted to Terminals

The rate at which heat is conducted through any part of the conductor is $-ak\,\frac{d\theta}{dx}$, where $\frac{d\theta}{dx}$ is the temperature gradient at that point. The negative sign indicates the physical fact that the sign of the direction of heat flow is opposite that of the temperature gradient; the positive direction being that corresponding with increasing values of x.

The temperature gradient at any point is found by differentiating equation 5 with respect to x, or

$$\frac{d\theta}{dx} = n\left[\frac{(\theta_0 - T_1)\cosh(L - x)n - (\theta_0 - T_2)\cosh xn}{\sinh Ln}\right] \quad (13)$$

Then the temperature gradient at the first terminal is found by making $x = 0$ in equation 13, or

$$\left.\frac{d\theta}{dx}\right]_{x=0} = n\left[\frac{(\theta_0 - T_1)\cosh Ln - (\theta_0 - T_2)}{\sinh Ln}\right] \quad (14)$$

Likewise the gradient at the second terminal, by making $x = L$, is

$$\left.\frac{d\theta}{dx}\right]_{x=L} = n\left[\frac{(\theta_0 - T_1) - (\theta_0 - T_2)\cosh Ln}{\sinh Ln}\right] \quad (15)$$

The rate of heat transfer in the positive direction, from terminal T_1 to the conductor, is

$$\left.-ak\,\frac{d\theta}{dx}\right]_{x=0}$$

and in the positive direction from the conductor to the terminal T_2 is

$$\left.-ak\,\frac{d\theta}{dx}\right]_{x=L}$$

The combined net rate of heat transfer to both terminals is then the difference between the rate of heat transfer from the conductor to the terminal T_2 and the rate of heat transfer from terminal T_1 to the conductor, or

$$H_t = \left[-ak\,\frac{d\theta}{dx}\right]_{x=L} - \left[-ak\,\frac{d\theta}{dx}\right]_{x=0}$$

Note that the signs take care of the actual direction of heat flow, which is usually negative at T_1.

Substituting values from equations 14 and 15, there results, after collecting terms and reducing,

$$H_t = 2\,ak\,n\left[\theta_0 - \left(\frac{T_1 + T_2}{2}\right)\right]\left(\tanh\frac{Ln}{2}\right) \quad (16)$$

Now, $(T_1 + T_2)/2$ is the mean temperature of the terminals, and for simplification let this be called T_0 and further, for θ_0 let its value $\frac{w}{c} = \frac{w}{n^2ak}$ by definition be substituted. Then the ratio of the heat absorbed by the terminals to the total heat generated $H = wL$, is

$$\frac{H_t}{H} = \left[\frac{2}{Ln} - 2\,ak\,n\,T_0\right]\tanh\frac{Ln}{2} \quad (17)$$

If T_0 is zero or negligible, which is a practical condition, then equation 17 reduces to

$$\frac{H_t}{H} = \frac{\tanh\dfrac{Ln}{2}}{\dfrac{Ln}{2}} \quad (18)$$

The ratio of the combined rate at which heat is transferred to the terminals to the total rate generated, for negligible terminal temperature elevation, for various values of Ln, as deduced by equation 18 is shown in figure 3.

Electrothermic Ammeters

Electrothermic ammeters in use before the development of the thermocouple type, described hereinafter, were of the hot wire expansion type. In the latter the conductors were designed to minimize as much as possible the effect of the terminals upon the conductor temperature, by making the conductors thermally long. In the thermocouple type the

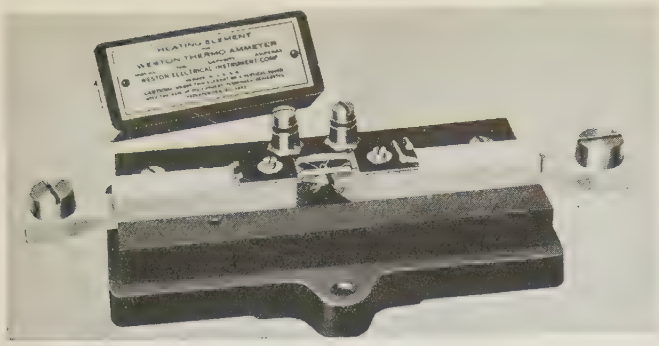


Fig. 6. The heating element of a commercial form of compensated thermocouple ammeter

terminal effect is purposely utilized by making the conductor so short thermally that most of the heat generated in it is conducted through it to the terminals. As a result the conductor temperature is based upon the terminal temperature rather than upon that of the surrounding air.

The instrument is designed to utilize as the measure of current, the difference in temperature between a point on the heated conductor and the terminals, produced by the rate of heat flow through the conductor against its thermal resistance. This is analogous to the measurement of current by means of a shunt in which use is made of the difference of potential produced by the passage of the current through it against its electrical resistance.

This feature permits the use of a very short heating conductor of small mass, resulting in very responsive indications, low electrical resistance and power consumption, and a minimum skin effect error.

Another feature in this instrument is the method for compensating for the effects of variations in air temperature and for differences in the terminal temperatures for conductors of any thermal length.

Thermocouple Ammeter (Simplest Form)

The use of a thermally very short heating conductor provides the simplest form of the type of thermocouple ammeter which resulted from this investigation.

Putting equation 11 into the following form

$$(\theta_1 - T_0) = \frac{v^2}{8k\rho} = \frac{I^2R^2}{8k\rho} \qquad (19)$$

where R is the resistance of the conductor and I the current through it to be measured, it is found that the equation shows that the difference in temperature between the center of the conductor and the terminals is proportional to the square of the current and, therefore, a measure of its effective value. Figure 4 is a diagrammatic sketch illustrating such an ammeter, using a sensitive indicating instrument connected to measure the thermo-electromotive force developed in a thermocouple which has its hot junction thermally connected to the heating conductor and its cold junction thermally connected to a terminal through a thin electrical insulator. The instrument indication is proportional to the temperature difference, but may be calibrated in amperes.

Thermocouple Ammeter (Compensated Form)

In any conductor regardless of its length, some of the heat generated in it is dissipated by convection as well as by conduction. Therefore, to determine how and to what extent this affects the accuracy of thermal instruments, and to provide means for compensating undesirable effects, it is necessary to consider both forms of heat dissipation.

Using equation 8 which applies to these conditions, and substituting I^2R^2 for v^2, there is obtained

$$\left(t_c - \frac{T_1 + T_2}{2}\right) = \frac{I^2R^2}{8k\rho}\left[\frac{2\left(1 - \dfrac{1}{\cosh\dfrac{Ln}{2}}\right)}{\left(\dfrac{Ln}{2}\right)^2}\right] - \frac{T_1 + T_2}{2}\left(1 - \frac{1}{\cosh\dfrac{Ln}{2}}\right) \qquad (20)$$

This shows that the difference in temperature between the center of the conductor and the terminals is in general not an exact measure of the current I, on account of the effect of the temperature elevation of the terminals, as shown in the last term of the equation, which should be compensated.

Figure 5 shows how this compensation is accomplished. H is the heating conductor connected between terminals, having a length L and a thermal constant n. Let c and c be 2 conductors each having corresponding constants L_1 and n_1 such that $Ln = L_1n_1$, and also thermally connected to the 2 terminals through thin electrical insulators ii.

The compensating conductors may be of the same material as the heater or of other materials or of a different length, so long as L_1n_1, that is, $L_1\left(\frac{c_1}{a_1k_1}\right)^{1/2}$ is the same as the corresponding values for the heating conductor.

A thermocouple has its hot junction connected to the center of the heating conductor, and its cold junctions to the center of each of the compensating conductors, which in turn are connected to an indicating instrument. Two conductors are used to simplify these connections.

The instrument will then give an indication proportional to the difference in temperature $(t_c - t_c')$ between the centers of the heating and compensating conductors, and it will be shown that this is a true measure of the effective value of the current passing through the heating conductor, independent of either the air or terminal temperatures.

To find the temperature difference between the center of the compensating conductors and terminals it is only necessary to make $I = 0$ in equation 20 and note that t_c becomes t'_c; then

$$\left(t_c' - \frac{T_1 + T_2}{2}\right) = -\frac{T_1 + T_2}{2}\left(1 - \frac{1}{\cosh\dfrac{Ln}{2}}\right) \qquad (21)$$

Subtracting equation 21 from equation 20, there is obtained

$$(t_c - t_c') = \frac{I^2R^2}{8k\rho}\left[\frac{2\left(1 - \dfrac{1}{\cosh \dfrac{Ln}{2}}\right)}{\left(\dfrac{Ln}{2}\right)^2}\right] \tag{22}$$

which, since I is the only variable in the equation, proves that the auxiliary conductors actually compensate for the effect of the temperatures of the terminals, whether they be equal or different, and for the effect of variations in temperature of the surrounding air.

If the compensating and heating conductors are made of unequal length or mass as shown, then, by making $Ln = L_1n_1$, they are thermally equivalent in all respects except heat capacity. That is, they can compensate exactly for steady state conditions but not for transients. To compensate for both it is necessary that the product of the mass and specific heat be the same for both. This latter condition is rarely necessary in practice, as the external and other disturbing temperature changes take place slowly.

The correctness of this result may be seen by purely physical reasoning. If the heating and compensating conductors are made thermally equivalent, then, since they are subject to the same conditions relative to terminals and surrounding air, they will be affected exactly alike. Therefore, the temperatures at their centers will always be equal as far as terminal and air effects are concerned. Any difference in temperature will then be the result of the current to be measured only.

For precise measurements it is of course necessary to mount the heating element in such a position that the heated air currents rising from the heated conductor do not impinge upon the compensating conductors, otherwise the 2 sets of conductors would not have the same ambient temperature and exact compensation could not be attained.

This is accomplished by placing the element horizontally and so mounted that the heating and compensating conductors are not one directly above the other in the same vertical plane.

Figure 6 illustrates a commercial form of the compensated thermocouple ammeter. The element as shown has a 50 ampere capacity and a voltage drop over the heater conductor of about 150 millivolts for full current for low frequencies.

The compensating conductors, bridging across the heating element, act as a shunted capacitance across the element, but in the lowest range instruments where shunted capacitance would cause greatest

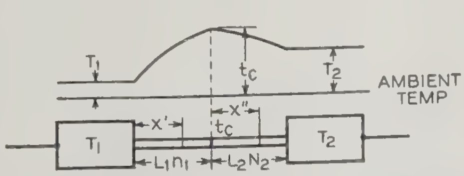


Fig. 7. Temperature distribution in a conductor consisting of 2 different metals or alloys, heated by a current or otherwise, as in an electrothermic ammeter in which the thermocouple is used also as the heating conductor

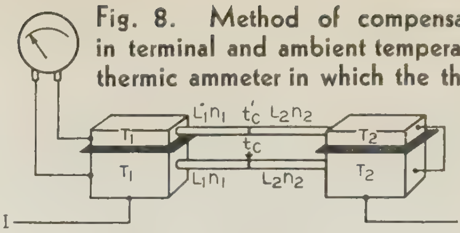


Fig. 8. Method of compensating for variations in terminal and ambient temperatures in an electrothermic ammeter in which the thermocouple is also used as the heating conductor

errors it is about 2.5 micromicrofarads, which results in negligible errors for frequencies up to 50 or 100 megacycles.

From the similarity of equation 22 to equation 19 for the condition with no convection, it will be noted that the effect of convection losses upon the difference in temperature used as the measure of the current, is merely to multiply the difference obtained without convection losses, namely, $\dfrac{I^2R^2}{8k}$, by the factor

$$\frac{2\left(1 - \dfrac{1}{\cosh \dfrac{Ln}{2}}\right)}{\left(\dfrac{Ln}{2}\right)^2}$$

which is a thermal constant of the conductor, regardless of terminal temperatures.

To illustrate the effect of convection losses, the values of this factor for various values of Ln are plotted in curve B in figure 3.

The ordinates are the values of the temperature difference where both convection and conduction are acting, relative to those values for the condition of conduction only, for various values of Ln.

Case of Conductor in 2 Parts

In bridge type electrothermic ammeters and some forms of radiation meters the heating conductor is made of 2 materials forming also a thermocouple as shown in figure 7, the hot junction being at the point where the 2 conductors are joined.

General Solution

Each of these 2 conductors may be considered as a conductor between terminals, the temperatures of which are T_1, t_c and t_c, T_2, respectively. Therefore, the general equation, 5, applies to each if the proper constants are used.

Let the constants of the conductors be L_1, a_1, k_1, c_1, n_1 and L_2, a_2, k_2, c_2, n_2, respectively.

To combine the equations of the 2 conductors and determine the temperature t_c of the junction it is only necessary to consider the feature common to both conductors, namely the rate of heat transfer across the junction. It is obvious that whatever heat leaves one conductor at the junction enters the other conductor and, therefore, they may be equated, or

$$a_1k_1\left.\frac{d\theta}{dx}\right]_{x'=L_1} = a_2k_2\left.\frac{d\theta}{dx}\right]_{x''=0}$$

In the general equation 13, for the temperature

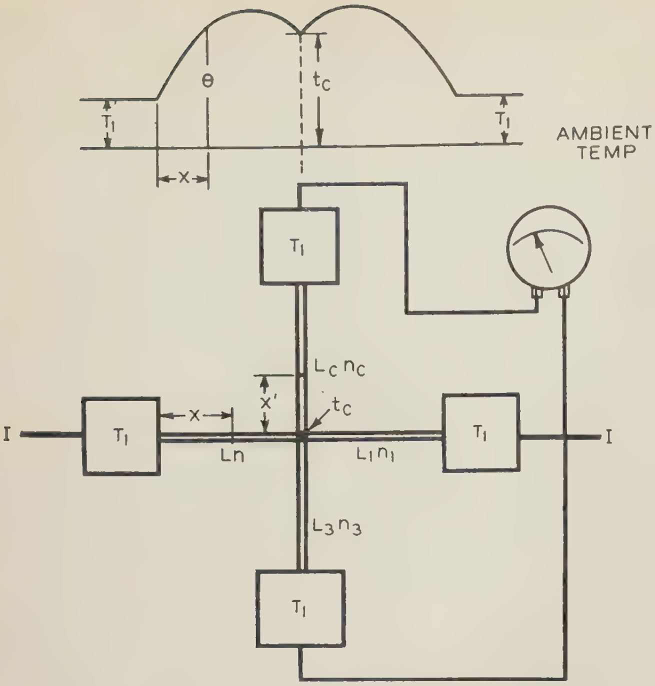


Fig. 9. Effect upon the temperature distribution in a conductor produced by the heat conducted away through a couple or other conductor attached to it

gradient, multiplying by a_1k_1 and substituting n_1, θ_1', L_1 and t_c for n, θ_0, L and T_2, respectively, and making $x' = L_1$, the following equation is obtained:

$$a_1k_1 \left.\frac{d\theta}{dx}\right]_{x'=L_1} = a_1k_1n_1 \left[\frac{(\theta_0' - T_1) - (\theta_0' - t_c)\cosh L_1n_1}{\sinh L_1n_1}\right] \tag{23}$$

For the second conductor make corresponding changes but make $x'' = 0$, and there is obtained

$$a_2k_2 \left.\frac{d\theta}{dx}\right]_{x''=0} = a_2k_2n_2 \left[\frac{(\theta_0'' - t_c)\cosh L_2n_2 - (\theta'' - T_2)}{\sinh L_2n_2}\right] \tag{24}$$

As stated above these heat rates are equal; therefore, equating 23 and 24 and after rearranging terms and remembering that $a_1k_1n_1^2 = c_1$ and $a_2k_2n_2^2 = c_2$, and that $\theta_0' = \frac{w_1}{c_1}$ and $\theta_0'' = \frac{w_2}{c_2}$, there results:

$$\frac{w_1}{n_1}\left[\frac{\cosh L_1n_1 - 1}{\sinh L_1n_1}\right] + \frac{w_2}{n_2}\left[\frac{\cosh L_2n_2 - 1}{\sinh L_2n_2}\right] = \frac{c_1}{n_1}\left[\frac{t_c \cosh L_1n_1 - T_1}{\sinh L_1n_1}\right] + \frac{c_2}{n_2}\left[\frac{t_c \cosh L_2n_2 - T_2}{\sinh L_2n_2}\right]$$

Rearranging to separate t_c,

$$t_c - \left[\frac{\dfrac{c_1T_1}{n_1 \sinh L_1n_1} + \dfrac{c_2T_2}{n_2 \sinh L_2n_2}}{\dfrac{c_1 \cosh L_1n_1}{n_1 \sinh L_1n_1} + \dfrac{c_2 \cosh L_2n_2}{n_2 \sinh L_2n_2}}\right] = \frac{\dfrac{w_1}{n_1}\left[\dfrac{\cosh L_1n_1 - 1}{\sinh L_1n_1}\right] + \dfrac{w_2}{n_2}\left[\dfrac{\cosh L_2n_2 - 1}{\sinh L_2n_2}\right]}{\dfrac{c_1}{n_1}\left[\dfrac{\cosh L_1n_1}{\sinh L_1n_1}\right] + \dfrac{c_2}{n_2}\left[\dfrac{\cosh L_2n_2}{\sinh L_2n_2}\right]} \tag{25}$$

This is the general equation for 2 conductors connected in series between terminals. A very practical case is that in which $L_1n_1 = L_2n_2 = Ln$, that is, when the 2 conductors are made thermally equivalent. Then equation 25 becomes

$$t_c - \left[\frac{\dfrac{c_1T_1}{n_1} + \dfrac{c_2T_2}{n_2}}{\left(\dfrac{c_1}{n_1} + \dfrac{c_2}{n_2}\right)\cosh Ln}\right] = \frac{\left(\dfrac{w_1}{n_1} + \dfrac{w_2}{n_2}\right)\left(\dfrac{\cosh Ln - 1}{\cosh Ln}\right)}{\left(\dfrac{c_1}{n_1} + \dfrac{c_2}{n_2}\right)} \tag{26}$$

And further if $T_1 = T_2 = T_0$ which is frequent in practice for this type of instrument, then, after making these substitutions and subtracting T_0 from both sides, there is obtained, after rearranging,

$$(t_c - T_0) = \left[\frac{\dfrac{w_1}{n_1} + \dfrac{w_2}{n_2}}{\dfrac{c_1}{n_1} + \dfrac{c_2}{n_2}} - T_0\right]\left(1 - \frac{1}{\cosh Ln}\right) \tag{27}$$

Comparing this equation with equation 7 for a homogeneous conductor, it shows that, for 2 different conductors having equal values of Ln connected in series between terminals having the same temperature, the same difference in temperature between the junction and terminals exists as for a uniform conductor between its center and its terminal, having a hyperbolic angle of 2 Ln, and a temperature constant

$$\theta_0 = \left[\frac{\dfrac{w_1}{n_1} + \dfrac{w_2}{n_2}}{\dfrac{c_1}{n_1} + \dfrac{c_2}{n_2}}\right]$$

Compensating Combined Heating and Thermocouple Conductors

Electrothermic ammeters and radiation meters, having heating conductors consisting of 2 parts of different metals or alloys in series to form at the same time a thermocouple, are affected by changes in the temperature of the surrounding air, and of its terminals, in a manner similar to uniform conductors and can be compensated in a similar manner.

In equation 26 subtract from each side the terminal function

$$\left[\frac{\dfrac{c_1T_1}{n_1} + \dfrac{c_2T_2}{n_2}}{\dfrac{c_1}{n_1} + \dfrac{c_2}{n_2}}\right]$$

and after rearranging there is obtained,

$$t_c - \left[\frac{\dfrac{c_1T_1}{n_1} + \dfrac{c_2T_2}{n_2}}{\dfrac{c_1}{n_1} + \dfrac{c_2}{n_2}}\right] = \left[\frac{\dfrac{w_1}{n_1} + \dfrac{w_2}{n_2}}{\dfrac{c_1}{n_1} + \dfrac{c_2}{n_2}} - \frac{\dfrac{c_1T_1}{n_1} + \dfrac{c_2T_2}{n_2}}{\dfrac{c_1}{n_1} + \dfrac{c_2}{n_2}}\right]\left(1 - \frac{1}{\cosh Ln}\right) \tag{28}$$

Now, if an auxiliary conductor, made exactly like the heating conductor but so connected that the thermo-electromotive force produced by it opposes that of the latter conductor, is thermally connected to but electrically insulated from the terminals, as shown in figure 8, then, just as for the single uniform conductor, the difference in temperature between junction points of the heating and auxiliary conductors is entirely independent of changes in temperature of the terminals or of the surrounding air.

This is shown by using the general equation, 28, and making w_1 and w_2, the heat generated in the auxiliary conductors, zero; then, since the corresponding values of L, n, and Ln, of the 2 sets of conductors are equal, by construction, and calling the temperature at the junction of the auxiliary conductor t_c', it follows that

$$t_c' - \frac{\frac{c_1T_1}{n_1} + \frac{c_2T_2}{n_2}}{\frac{c_1}{n_1} + \frac{c_2}{n_2}} = -\left[\frac{\frac{c_1T_1}{n_1} + \frac{c_2T_2}{n_2}}{\frac{c_1}{n_1} + \frac{c_2}{n_2}}\right]\left(1 - \frac{1}{\cosh Ln}\right)$$

Subtracting this from equation 28, then

$$(t_c - t_c') = \left[\frac{\frac{w_1}{n_1} + \frac{w_2}{n_2}}{\frac{c_1}{n_1} + \frac{c_2}{n_2}}\right]\left(1 - \frac{1}{\cosh Ln}\right) \quad (29)$$

which proves the statement made above. This equation has the same form as that obtained in a similar manner from equation 7 for a single homogeneous conductor; the quantity

$$\left[\frac{\frac{w_1}{n_1} + \frac{w_2}{n_2}}{\frac{c_1}{n_1} + \frac{c_2}{n_2}}\right]$$

in equation 29 corresponds to the temperature θ_0 in equation 7.

Effect of Heat Conducted Away Through a Couple or Other Conductor

Referring to figure 9, assume for simplicity that all terminals have the same temperature elevation T_1 above the surrounding air, and that the characteristics of the 2 halves of the heating and thermocouple conductors are equal, respectively, that is, $L_1n_1 = Ln$ and $L_3n_3 = L_cn_c$.

As a result of symmetry it is only necessary to examine one half, L and L_c of the 2 conductors, and the junction may be treated as the second heat absorbing terminal at a temperature elevation t_c, corresponding to T_2 in the general equations.

The temperature gradient at the junction t_c is obtained by making $x = L$ in equation 13 and replacing T_2 by t_c,

$$\frac{d\theta}{dx} = -n\left[\frac{(\theta_0 - t_c)\cosh Ln - (\theta_0 - T_1)}{\sinh Ln}\right] \quad (30)$$

The rate at which heat is transferred from the heater to the couple conductor at t_c is $-ak\frac{d\theta}{dx}$.

Now the couple wire can be considered as a heating conductor in which the heat generated is zero, that is, $\theta_0 = 0$ so that the gradient along L_c can be determined by placing $\theta_0 = 0$ in equation 13; substituting L_cn_c for Ln; t_c for T_1; and T_1 for T_2; then the gradient at t_c in the couple conductor at the junction where $x' = 0$ is

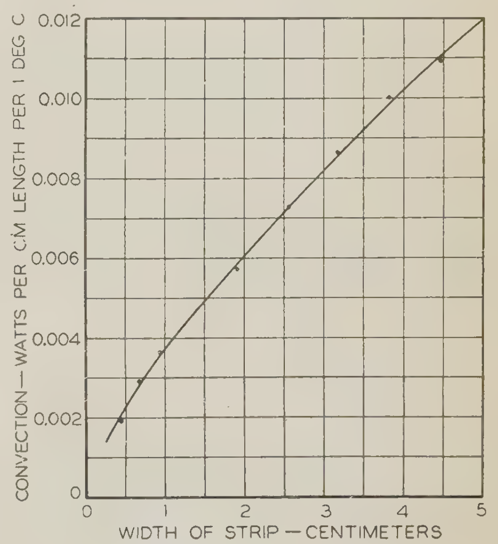
$$\frac{d\theta}{dx'} = n_c\left[\frac{t_c \cosh L_cn_c - T_1}{\sinh L_cn_c}\right] \quad (31)$$

and the rate at which heat is conducted away from the junction t_c by the couple conductor is then $-a_ck_c\frac{d\theta}{dx'}$.

Since the 2 expressions (equations 30 and 31) represent the heat flow at the same point, they are equal, that is

$$\frac{akn}{\sinh Ln}\left[(\theta_0 - t_c)\cosh Ln - (\theta_0 - T_1)\right] = \frac{a_ck_cn_c}{\sinh L_cn_c}\left[t_c \cosh L_cn_c - T_1\right] \quad (32)$$

To simplify this equation, assume $T_1 = 0$, which is usually the case approximately for the construction



Thickness of strip—0.38 millimeter

Fig. 10. Convection loss in air from thin flat strips of various widths, supported horizontally, and lying in the vertical plane, in watts per centimeter length per degree centigrade above air temperature. Average for 100 degrees centigrade

under consideration, and designate the 2 constant coefficients as M and N, respectively, and solve for t_c, then

$$t_c = \frac{M\theta_0(\cosh Ln - 1)}{M \cosh Ln + N \cosh L_cn_c} \quad (33)$$

Now, when no couple conductor is connected to the heating conductor, the temperature of its center t_0 is found by making $N = 0$ in equation 33, then

$$t_0 = \theta_0\left[1 - \frac{1}{\cosh Ln}\right]$$

The ratio of these 2 temperatures is then

$$\frac{t_c}{t_0} = \frac{M \cosh Ln}{M \cosh Ln + N \cosh L_cn_c} \quad (34)$$

which is the ratio of the temperature elevation as diminished by the presence of the couple, to that which it would have if no couple had been attached.

The interesting case is when the couple wires have the same length as the heater and the same constants a, k, n, etc., which makes $M = N$, and $Ln = L_cn_c$.

Making these substitutions, then $t_c/t_0 = 1/2$, that is, the temperature of the center of the heater above the surrounding air is reduced to $1/2$ that which it

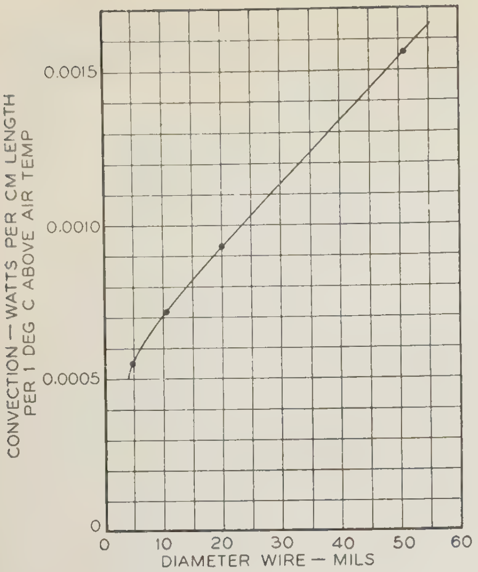


Fig. 11. Convection loss in air from round wires, supported horizontally, in watts per centimeter length per degree centigrade above air temperature. Average for 100 degrees centigrade

would be if no couple were connected, when couple and heater are thermally equivalent, as is usually the case in the so-called thermo-cross for measurements of small currents.

Heat Conducted to Terminals in a Thermo-Cross

The temperature gradient in the heater wire of length L from terminal T_1 to the couple junction in figure 9 is found by differentiating equation 5 as given in equation 13 and substituting t_c for T_2. Then the heat transferred to the heater terminal is

$$H_h = -ak\left.\frac{d\theta}{dx}\right]_{x=0} = akn\left[\frac{(\theta_0 - t_c) - (\theta_0 - T_1)\cosh Ln}{\sinh Ln}\right]$$

Assume the terminal to be at air temperature; that is, $T_1 = 0$. Then

$$H_h = akn\left[\frac{\theta_0(1 - \cosh Ln) - t_c}{\sinh Ln}\right] \tag{35}$$

From equation 33 it is deduced that

$$t_c = \frac{\theta_0(\cosh Ln - 1)}{2\cosh Ln}$$

since $M = N$, by assuming that the conductors of heater and couple in the thermo-cross are equal in length and thermally equivalent.

Substituting for t_c in equation 35 its value, the following equation results:

$$H_h = akn\theta_0\left[\frac{(1 - \cosh Ln) - \left(\dfrac{\cosh Ln - 1}{2\cosh Ln}\right)}{\sinh Ln}\right]$$

Rearranging, and collecting terms,

$$H_h = -\frac{akn\theta_0}{2}\left[\tanh\frac{Ln}{2} + \tanh Ln\right] \tag{36}$$

The rate of heat transfer from each couple wire to its terminal is $H_c = -ak\dfrac{d\theta}{dx}$, when $x' = L$, and is found by changing T_1 to t_c, and T_2 to T_1 and also making $\theta_0 = 0$ in equation 13, since the origin of co-ordinates for the couple is at the thermojunction having a temperature t_c.

Further, assume the terminals are at air temperature, that is, $T_1 = 0$.

Then,

$$H_c = akn\left[\frac{t_c}{\sinh Ln}\right]$$

Now, from equation 33,

$$t_c = \frac{\theta_0(\cosh Ln - 1)}{2\cosh Ln}$$

Substituting and reducing,

$$H_c = \frac{akn\theta_0}{2}\left[\frac{\tanh\dfrac{Ln}{2}}{\cosh Ln}\right] \tag{37}$$

The combined rate at which heat is conducted from the heater and the couple to their terminals is then

$$H_t = H_c + (-H_h) = akn\theta_0\left[\tanh\frac{Ln}{2} + \tanh Ln + \frac{\tanh\dfrac{Ln}{2}}{\cosh Ln}\right]$$

Combining terms and simplifying,

$$H_t = akn\theta_0 \tanh Ln \tag{38}$$

It is interesting to note, by referring to equation 16, that the combined heat dissipated by conduction to the terminals in a symmetrical thermo-cross is the same as it would have been had no couple been attached, remembering that L in the thermo-cross is $^1/_2$ the total length between terminals.

Practical Applications

Shunts With Thermally Short Conductors

In shunts having very short conductors, or conductors from which the proportion of the heat lost by convection is relatively very small, the temperature relations can be computed by equations 9 to 12.

For example, consider an ordinary 50 millivolt shunt having a number of short manganin strips placed close together with negligible air cooling.

k = thermal conductivity = 0.20 watt per centimeter cube per degree centigrade
ρ = resistivity = 47×10^{-6} ohm per centimeter cube

Then the temperature difference between the center of the conductors and either terminal if they have equal temperatures, or their mean temperature if different, is, by equation 11,

$$(t_c - T_0) = \frac{v^2}{8k\rho} = \frac{(0.050)^2}{8 \times 0.2 \times 47 \times 10^{-6}} = 33.2 \text{ degrees centigrade}$$

This is the maximum elevation in temperature, under the assumed conditions, above that of the terminals, in a manganin conductor connected be-

tween them, carrying a direct current of a magnitude to produce a drop of 50 millivolts between terminals, regardless of the length of the conductor.

Shunt With a Thermally Long Conductor

Assume again a 50 millivolt shunt having a single manganin conductor mounted with the conductor in the vertical plane for maximum cooling, and let it have the following constants:

L = length = 10 centimeters
width = 1 centimeter
thickness = 0.5 millimeter
ρ = resistivity = 47×10^{-6} ohm per centimeter cube
k = thermal conductivity = 0.2 watt per centimeter cube per degree centigrade
C = convection loss per centimeter length = 0.00375 watt; watt from figure 10
a = cross sectional area = 0.05 square centimeter

As shown in equation 8 the temperature relations depend upon the value of the hyperbolic angle Ln subtended by the conductor, or

$$Ln = L\left(\frac{c}{ak}\right)^{1/2} = 10 \times \left(\frac{0.00375}{0.05 \times 0.2}\right)^{1/2} = 6.1 \text{ hyperbolic radians}$$

Now, in figure 3, in which curves A and B are computed from equations 18 and 8, respectively, curve A shows that for an angle of 6.1 hyperbolic radians, 33 per cent of the heat is conducted to the terminals when they are at air temperature; and curve B, that the center of the conductor has a temperature elevation above that of the terminals equal to 20 per cent of the value it would have if there were no air cooling, that is, 20 per cent of 33.2 degrees centigrade found above for a conductor with no convection, or 6.6 degrees centigrade. Thus the air cooling in such a shunt causes a depression in the temperature of 26.6 degrees centigrade.

Convection losses for conductors of greater widths than about 1.5 inches, directly exposed to air, may be computed by using a convection constant of 0.0011 watt per square centimeter per degree centigrade. For narrower strips and for wires, the effective cooling area becomes increasingly larger than the actual superficial area, and data for these are given in figures 10 and 11, respectively.

These values, of course, apply only to single conductors with no other bodies nearby to prevent free circulation of air.

When 2 or more strips are used, placed relatively close together, the cooling effect is very much reduced and as the number increases, it becomes practically negligible relative to the amount of heat generated.

In the illustration given above, with a single long strip freely exposed to the air, the air cooling of the conductor accounted for 67 per cent of the total cooling.

In ordinary 50 millivolt commercial high range shunts with multiple strips, which are relatively short thermally, usually much less than 10 per cent of the heat is dissipated from the strips by air cooling, the remainder being conducted to the terminals and then to the bus bars. Shunts as usually constructed, therefore, are not self-cooling, but depend upon proper bus bar construction for this purpose. Multiple strips are used in shunts rather than single conductors, not primarily for cooling purposes, but for mechanical reasons, to make a more perfect contact between the entire cross section of the conductor and the terminal than would be possible with a single conductor.

Thermal Conductivity

Equation 11 can be used to determine the thermal conductivity of a material.[3]

The material is made into a conductor, thermally short, of uniform cross section and connected between 2 relatively massive terminals.

From its measured length and cross section, and its resistance as determined by the drop across it produced by a known current, its resistivity ρ in ohms per centimeter cube can be computed.

Then the temperature difference $(t_c - T_0)$ between the center of the conductor and a terminal produced by a known voltage drop v in volts is measured, preferably by means of a calibrated thermocouple.

Then rearranging equation 11, the thermal conductivity in watts per degree per centimeter cube is obtained:

$$k = \frac{v^2}{8\rho(t_c - T_0)}$$

Appendix I—List of Symbols

a = cross sectional area of conductor, square centimeters
c = rate of heat dissipated by surface loss per unit length of conductor per degree temperature elevation above cooling medium (watts per centimeter per 1 degree centigrade). This surface loss results from convection and radiation, but since the radiation under the circumstances is very small relative to convection losses, the total loss will be designated convection for simplicity.
H_t = rate at which heat is transferred to terminals (watts)
k = thermal conductivity of conductor (watts per centimeter cube per 1 degree centigrade)
L, L_1, etc. = lengths of conductors
n = $(c/ak)^{1/2}$ = hyperbolic radians per unit length of conductor
R = resistance of conductors, ohms
t_c, t'_c, etc. = temperatures at centers of conductors above ambient temperature
T_1 and T_2 = temperatures of terminals above ambient temperature
v = voltage drop over conductor, volts
w, w_1, w_2, etc. = rate of heat generated per unit length of conductor, watts per centimeter
x = distance from terminal T_1 to any point on conductor
y = distance from the center of the conductor to any other point
ρ = electrical resistivity of conductor, ohms per centimeter cube
θ = temperature of any part of conductor above ambient temperature
θ_0, θ_0', θ_0'' = temperature elevation of conductors if no cooling by conduction occurred

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High Power Audio Transformers

A brief outline of the essential characteristics of high power audio transformers for class B amplification (tubes connected in push-pull fashion with their grid voltages of such value that the anode current is zero when there is no signal) is given here together with a brief description of the units used in the third and fourth stages of radiobroadcast station WLW.

By
J. F. PETERS
FELLOW A.I.E.E.

Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

HIGH POWER audio transformers do not differ materially from large transformers for converting power at 60 cycles. They differ principally in physical proportions of copper and iron, and require greater care in minimizing the internal distributed capacitance.

Since an audio transformer must operate over a wide range of frequencies and be capable of handling the full output at any one frequency or any combination of frequencies, the problem of obtaining sufficiently low leakage reactance and sufficiently low magnetizing current is the reason for making the proportions different from those of transformers for use at commercial power frequencies. The leakage reactance must be made sufficiently low to give good performance at high frequency, and the magnetizing current must be made sufficiently low to give good performance at the low frequency end of the range. To produce sufficiently low reactance to give satisfactory operation at high frequencies requires using a small number of turns for a given voltage, which results in a magnetic circuit of relatively large cross section. To obtain sufficiently low magnetizing current at low frequencies still further increases the cross section of the magnetic circuit.

These transformers are supplied by tubes that pass current in only one direction, and generally it is not possible to maintain a perfect balance between the 2 tubes supplying the alternate half cycles. This results in the equivalent of a direct current flowing through the primary winding. In order to prevent the unbalance of current from producing a heavy biased magnetic flux in the core, air gaps were provided in the units described later in this paper. Although air gaps in the core increase the alternating magnetizing current, they make it possible to design the core and coils so that the iron does not become saturated and produce harmonics in the magnetizing current.

The effective resistance of the windings of these transformers is low, first, because of the relatively small number of turns resulting in a small number of ampere-turns and therefore low-density leakage magnetic field cutting the conductors; and second, because the conductors are made of small dimensions in the direction at right angles to the flux lines, thus resulting in a low ratio between high frequency resistance and low frequency resistance.

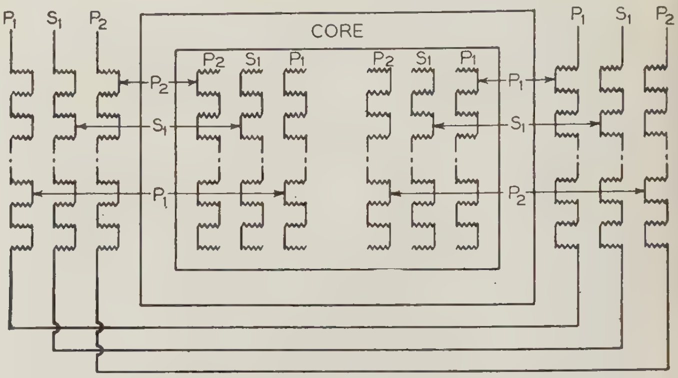

Fig. 1. Schematic diagram showing arrangement of windings in 180 kw fourth stage transformers

P and *S* designate primary and secondary windings, respectively

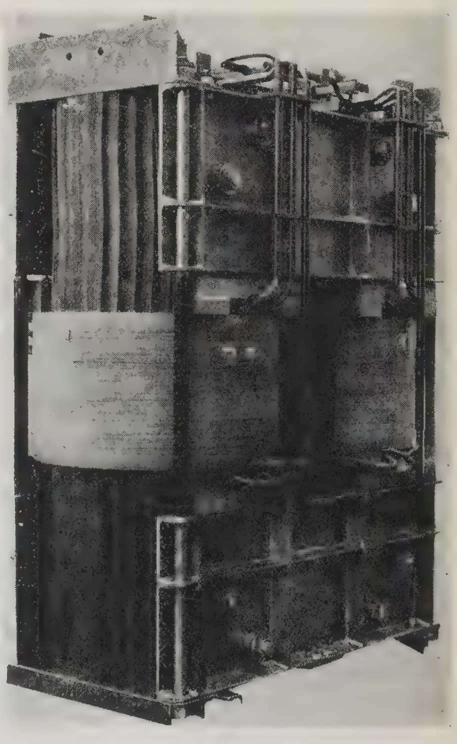

Fig. 2. One of the 180 kw fourth stage transformers out of its case

In producing the total output for radiobroadcast station *WLW*, 4 stages of amplification are required. Only the last 2 stages are described here, the first 2 stages being of quite small output. In determining the maximum permissible reactance for each of the last 2 stages, the total permissible value was determined and it then was proportioned between the 2 units in the manner that would meet most easily the maximum permissible value.

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It is desirable to have the output of the combined amplifying stages reproduce accurately all input frequencies in their relative magnitudes. It is of course not practical to accomplish this. Freedom from distortion is more important in certain parts of the frequency range than in others. Distortion in frequencies below 100 cycles and above 10,000 cycles, if not excessive, does not alter seriously the quality of reproduction. When designing the audio transformers for station *WLW*, the quality desired necessitated limiting the distortion to 5 per cent between 100 and 5,000 cycles and to 22 per cent at 30 cycles and at 10,000 cycles.

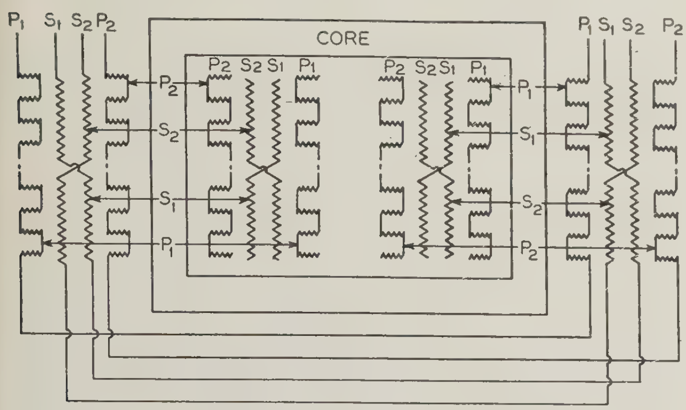

Fig. 3. Schematic diagram showing arrangement of windings in $7^1/_2$ kw third stage transformers

P and *S* designate primary and secondary windings, respectively

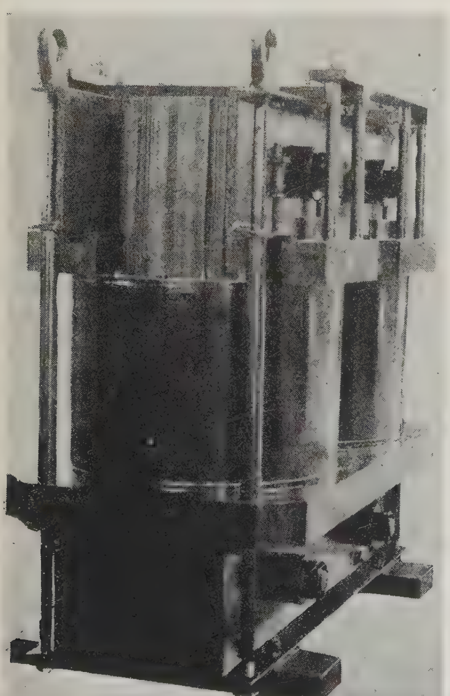

Fig. 4. A complete $7^1/_2$ kw third stage transformer

The requirements of reproducibility at the high frequency end of the range have more influence on the design of the transformers than do those at the low frequency end. The leakage reactance in the units, which is proportional to frequency, reduces the amplitude of delivered voltage. The load on the transformers is made up of various frequencies superimposed; but by limiting the reactance to such a value that the distortion will not exceed 22 per cent when supplying full load at 10,000 cycles, then when the load consists of a combination of frequencies, none of any appreciable magnitude exceeding 10,000 cycles, the required performance specifications will be met.

The circuits that the transformers feed into have the characteristics of a resistance; therefore, they supply loads at unity power factor. The regulation of the units as calculated for unity power factor at their rated loads then is a measure of their amplitude performance.

The total regulation at 22 per cent at 10,000 cycles was split arbitrarily 13 per cent for the fourth stage and 9 per cent for the third stage. The maximum permissible reactance for the fourth stage then was square root of $[100^2 - (100 - 13)^2]$ or 49 per cent and for the third stage 41 per cent, when delivering the full output of the units at 10,000 cycles. It was found when designing the units that the 49 per cent on the large unit could be appreciably lower, with the result that the combined errors of the 2 stages at 10,000 cycles should not exceed 14 per cent.

Performance tests were not made on individual transformers. Tests on the complete combination of all stages including the transformers and tubes indicated excellent results.

The fourth stage audio transformer for station *WLW* has a nominal rating of 180 kw. This unit has 2 input or primary windings each for 10,200 volts (crest) and one secondary or output winding of 6,000 volts (crest). The arrangement of the windings is indicated by figure 1, and the unit out of its tank is shown in figure 2. Since the 2 primary windings are supplied by separate tubes and therefore receive current on alternate half cycles, it was necessary to interlace these 2 windings symmetrically with the secondary winding. All 3 windings consist of circular pancake coils. Each primary winding consists of a stack of coils on each leg of the transformer as shown by figure 1. The stack of coils having the larger diameter on one leg is connected in series with the stack having the smaller diameter on the other leg, the secondary winding being between the inner and outer primary windings. All 3 windings are made of thin copper ribbon. The individual primary coils consist of 2 turns each, and the secondary coils of 3 turns each.

The assembled unit as shown in figure 2 weighs 27,000 pounds. Some idea of the proportion of copper and iron can be obtained from the fact that of the 27,000 pounds, the magnetic circuit contains 25,700 pounds of sheet steel. This transformer is placed in a boiler-iron tank and operates in oil.

The third stage transformers have a nominal rating of $7^1/_2$ kw each, 2 of these units being required for this stage. Each of these transformers has 2 primary and 2 secondary windings. The 2 primary windings are supplied from separate tubes, and the 2 secondary windings supply the grid voltage to the tubes for the fourth stage. The 2 primary windings receive current in alternate half cycles and must feed into each of the secondary windings; therefore, it was necessary to interlace all 4 windings. The arrangement of the windings is shown by figure 3.

The secondary windings are made up of single-layer helical coils. The coils are broken in the center and cross-connected so that on each leg the average coupling to the primary windings is the same for both windings. The 2 primary windings are made up of

pancake coils. One of these units is shown in figure 4. They are air insulated and are not placed in a container. Their total weight is 4,200 pounds each.

Electrical Equipment for Waterworks Systems

The application of supervisory control equipment and electric pump drive to municipal waterworks systems results not only in greatly improved operation, but also in a reduction in operating costs. Existing waterworks systems may be modernized and many improvements secured by the application of various types of electrical equipment. As an illustration of the benefits which may be obtained, a description is given of the modernization of the waterworks system of the city of Pittsburgh, where electric operation of pumps, together with supervisory control, remote metering, and remote indication, are now used.

By
S. A. CANARIIS
MEMBER A.I.E.E.

Bureau of Water, City of Pittsburgh, Pa.

THE first known developments in waterworks engineering are recorded by the ancient nations as the digging of wells for obtaining a supply of water. Probably the most famous of these is Joseph's well in Cairo, Egypt, not only on account of its depth of 297 feet through solid rock, but also because it was pumped by means of endless chain buckets operated by mule power. Later developments brought the building of storage reservoirs and aqueducts, of which there are well preserved examples dating from before the birth of Christ. The Romans had an organized water department in charge of a water commissioner, and developed many phases of waterworks practice which are used today.

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During the middle ages the art declined, until the "Black Death" plague, taking a toll of over 40,000,000 lives, aroused the nations to the necessity of improved sanitary conditions. The developments were extremely slow, and it was not until steam engine driven pumps and cast iron pipe were available for general use, that the modern waterworks systems began to take form. Filtration of water was known and practiced in Europe in the early part of the 19th century, but was not generally accepted in this country until about 1900. Today, practically every urban community in the United States has an adequate supply of water, properly treated, and delivered at satisfactory pressures and in sufficient quantities to meet all demands of health hygiene and fire protection. There are now in this country approximately 9,000 municipally owned and operated water supplies.

Recent Developments

One of the most evident features of private plant modernization is the use of labor saving devices, with the replacement of manually operated equipment by automatically controlled equipment. This move is not only one of economy, but is often essential in order to eliminate errors and faults in operation and production which are results of the uncertainty of manual control. While no claim is made for perfection in machinery, equipment, and control for waterworks purposes, there is no doubt that the equipment which can be purchased today has been developed to such a degree of simplicity, efficiency, reliability, and safety that no water company, be it private or municipal, can afford to overlook the economic advantages offered by its use in modernization of its plants.

An example of this may be found in the development of the centrifugal pump, where improved design has increased the efficiency of certain sizes by more than 20 per cent during the past 10 years. Not only has the initial efficiency been increased, but much progress has been made in maintaining the efficiency for a reasonable length of time. The improved construction of bearings, with use of temperature relays, and also the use of metallic packing for glands, has made continuous attendance unnecessary, and after the initial running-in period, a weekly inspection is all that is required.

Another marked improvement in waterworks equipment is the development of the rotary cone type valve to serve as a combination of check and gate valve. Operated at adjustable speed by electric or hydraulic motor, and controlled hydraulically or electrically, it can operate entirely automatically as required for proper pump and pipe line protection. The development of this type of valve, has, more than any other equipment, made the electrically driven centrifugal pump practical for waterworks use and particularly for automatic station application, as it provides a protection in case of power failure or automatic shut-down which was impossible to obtain with the old type of check valve. That this protection is necessary can be realized when it is considered that the surge wave in pipe may reach veloci-

ties of 3,600 to 4,200 feet per second, adding surge pressures of 50 to 250 pounds above normal operating pressures. To prevent the pumps and station piping, as well as the outside pipe lines, from being subjected to such excessive pressures, modern waterworks successfully employ the cone type valve which, when properly timed, keeps water hammer and surges well within safe limits.

Trend Toward Electrically Operated and Controlled Stations

The trend during the past 10 years has definitely been toward electrically operated pumping stations, partly due to the much smaller investment required as compared to prime mover installations, partly due to improved equipment, and partly due to the general decrease in rates for electric power. While this is especially true in smaller water companies, there are outstanding examples of complete electrification of all pumping stations in large, progressive cities, such as in Baltimore, which abandoned its last steam plant about 5 years ago. The waterworks management of this same city has made extensive and successful use of automatic control for its pumping stations.

The economical and practical electrification of pumping stations has again made it possible for the waterworks managements to choose the most advantageous locations for their plants, as the excessive space required for a steam plant, the coal supply facilities, smoke nuisance, etc., are no longer factors to be considered. The result is better utilization of the distribution system, and the possibilities of improving service, by proper location of the pumping stations in relation to the load and distribution system. The water systems thereby become flexible, and unpredictable expansions of communities no longer need to be served through excessive capital expenditures, but often may be handled by the addition of a local pumping or booster station.

It is only natural to expect an increase in the number of a large community's pumping stations, and as the number of stations increases, the system becomes a parallel to the modern electric power utility, and the problem requires treatment along similar lines. A customary division of a waterworks department is: (1) filtration division, responsible for providing an adequate supply of pure water; (2) mechanical division, for maintenance and operation of pumping stations; and (3) distribution division, responsible for the proper delivery of the water and metering of the services. The similarity in functions of an electric power company's generating, substation, and distribution departments is quite evident. The necessity and advantage of a technical and co-ordinating body, such as a system operators department, have been definitely established by the electric power companies.

The development of supervisory control systems has made it possible and practical to operate or supervise operation of the entire system from a central office, and this feature has been largely responsible for the decrease in power outages and the quick restoration of service, as well as economy in operation from properly planned and executed load control.

Waterworks System of the City of Pittsburgh

While it is true that no 2 communities have the same problems in water supply, pumping, and distribution, there is a certain similarity in many localities, which enables waterworks engineers to benefit from the experience of other communities. A typical system set-up will therefore be used to show the

Pumping Station	Drive	Pressure Control	Planned Future Control
Ross	Steam	Manual	Manual
Aspinwall	Steam	Manual	Remote
Brilliant	Electric	Manual	Supervisory
Howard St.	Electric	Manual	Supervisory
Herron Hill	Electric	Manual	Supervisory
Mission St.	Steam	Manual	Supervisory
Saline	Electric	Supervisory	Supervisory
Lincoln	Electric	Automatic	Automatic
Highland	Electric	Automatic	Automatic

Reservoir or Tank	Elevation Above Pittsburgh Datum of 696.5 feet	Total Capacity in Million Gallons
Clear Water Basin	51.0	41.2
Lanpher Res.	274.5	150.9
Highland Res. No. 1	368.0	117.3
Highland Res. No. 2	276.0	124.6
Brashear Res.	678.0	11.0
McNaugher Res.	513.5	5.39
Spring Hill Tanks	513.5	0.94
Herron Hill Res.	654.3	1.5
Bedford Res.	399.4	2.71
Allentown Tanks	596.0	3.17

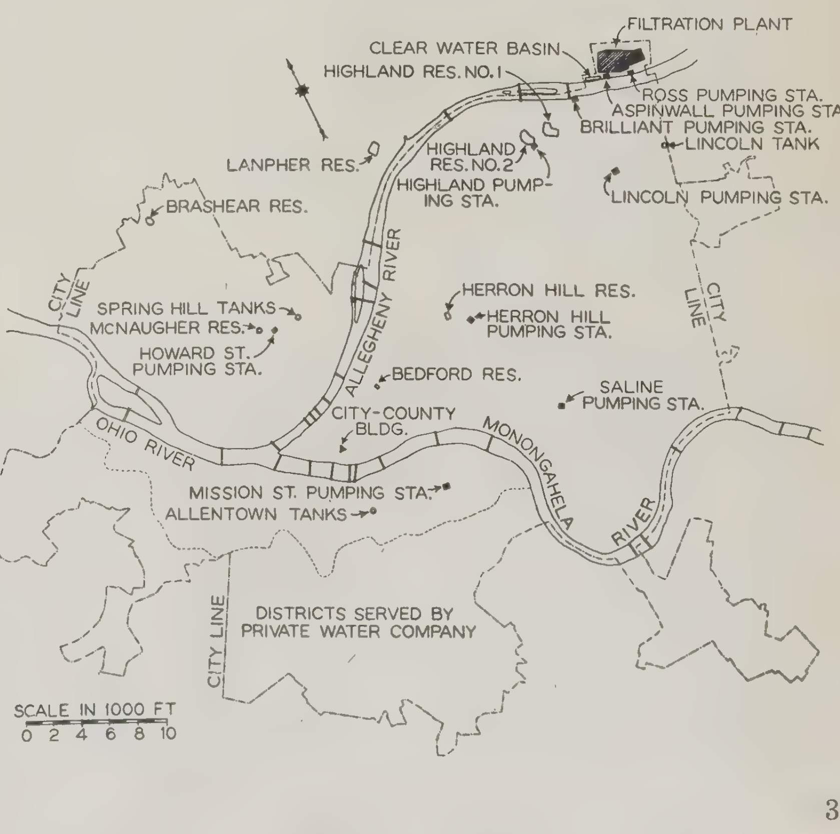

Fig. 1. Map of the city of Pittsburgh, Pa., showing the pumping stations and reservoirs of the bureau of water, department of public works

possibilities and advantages of central control points. The system is that of the city of Pittsburgh, Pa., which, due to the rugged topography of the district, together with the separation of zones by rivers, deep ravines, and valleys, presents an unusually difficult problem. The variation in elevation of the various zones served is almost 700 feet, and the establishing of 9 independent pressure zones has been found essential for the proper and safe delivery of water. Refer to figure 1 for a map of the stations and reservoirs described in the following paragraphs.

The raw water is obtained from the Allegheny River, and is pumped through the low head Ross pumping station to the sedimentation basins which are part of the filtration plant; the water then flows by gravity through the filters to the "clear water basin" where it receives the chlorine treatment. This part of the system is properly known as the "preparation system."

From the clear water basin the filtered and purified water is pumped by the Aspinwall pumping station to the Lanpher reservoir on the North Side, and by the Brilliant pumping station to Highland reservoir number 1, known as the "high service," and to Highland reservoir number 2, which, interconnected with Lanpher reservoir, is known as the "low service." These 2 services and their pumping stations constitute the "primary distribution system."

The "secondary distribution system" comprises 6 "secondary" pumping stations and their "services" or pressure zones, as follows: (1) Howard Street pumping station, pumping to Brashear reservoir and Brashear service, and also to McNaugher reservoir and Spring Hill tanks furnishing the McNaugher service; (2) Mission Street pumping station, pumping to Allentown tanks and Allentown service; (3) Herron Hill pumping station pumping to Herron Hill reservoir and Herron Hill service, and also to Bedford reservoir and Bedford service; (4) Saline pumping station, pumping directly into 3 segregated high areas which were formerly part of the Herron Hill service and relieving excess pressure automatically into the Herron Hill service; (5) Highland pumping station, pumping directly into a distant part of the Herron Hill service, with open connection to this service; and (6) Lincoln pumping station, pumping directly into the Lincoln service with overflow to the Lincoln tank.

Power Supply and Pump Drives

Of these stations, the Highland and Lincoln pumping stations are fully automatic, electrically operated, the former operating continuously, and the latter operating as required to maintain proper tank level and district pressures. Saline pumping station is also electrically operated, but is entirely dispatched over a 2-wire supervisory-control system from the attended Herron Hill pumping station, approximately 2 miles distant. Brilliant, Howard Street, and Herron Hill pumping stations are attended, electrically operated stations. Ross, Aspinwall, and Mission Street pumping stations are attended, steam driven stations using coal for fuel.

Aspinwall and Mission Street pumping stations are equipped with vertical triplex pumping engines, but their electrification in the near future is indicated by the ever mounting cost of repairs and maintenance of this obsolete type of equipment. A substantial saving in operating cost can be realized by the electrification of Mission Street station, while the economical electrification of Aspinwall station is dependent chiefly upon the power costs obtainable at that time.

The Ross pumping station is equipped with modern turbine drives. It furnishes a considerable amount of low pressure steam for heating of the filtration plant, including its underground galleries, and also furnishes direct current for the operation of the filtration plant auxiliaries. It therefore is necessary to maintain operating labor at this station.

Remote Control, Metering, and Indication Used

The Aspinwall station, if electrified, will be unattended, and operated entirely by remote direct-wire control from Ross station, the distance between the 2 stations being only 1,500 feet. The Brilliant station which now has an operating force of 10 men will also become unattended and will be operated over supervisory control from Ross station. A glance at the map of the water bureau's facilities, with an understanding of the previous description of the functions of these parts of the system, will show the logic of such an arrangement. This provides a single point for controlling the water output of the raw water station and the primary water pumping stations in co-ordination with the adjacent filtration division. These must all operate in sequence and, for the purpose of economy, at nearly the same rates.

The bureau of water now maintains an office, the so-called "day and night" office, in the City-County

Fig. 2. Control switchboard for Saline pumping station, showing the supervisory control panel at left and the automatic control cubicles beyond

Building, which receives and records reservoir levels and other information pertaining to service from the distribution system; it also handles all service complaints, and is in general responsible for transmitting pertinent service information to the various agencies. In view of its present function, it is evident that the direct control of the operation of secondary system pumping stations should be placed in the hands of this office. The city is, therefore, contemplating establishing a distribution system dispatcher's office in connection with this "service" center, from which the Howard Street, Mission Street, Herron Hill, and Saline pumping stations will be operated over supervisory control. Again referring to the map, it is clearly evident that the relative location of the 4 stations and the City-County Building makes this arrangement practical and logical.

All circuits for supervisory control will be 2 wire channels rented from the Bell Telephone Company, an arrangement which has proved economical and practical compared with the construction and maintenance of private lines.

In connection with supervisory control of water pumping stations it is necessary to mention the development of remote metering equipment, because few applications of this type of control would have been practical or possible without reliable means of ascertaining the water conditions in remote points of the system. Many forms of such devices have been placed on the market, but only in the past few years has it been possible to obtain a device which is sufficiently simple in design and rugged in construction to be accepted confidently by the waterworks engineers. The use of time as a measuring unit eliminates inaccurate readings. The adaptability of the equipment to transmit any information desired, be it either flow, pressure, voltage, or any other form of metered energy, makes this form of equipment of inestimable value in the promotion of the proposed modernization of water plants and systems. It enables the dispatcher to visualize the various system conditions at all times.

As an example of the necessity for remote indication of water conditions as well as the advantages of remote control of related pumping stations, the service to the Squirrel Hill district in Pittsburgh will be described briefly. This district was formerly served from the Herron Hill reservoir, until the increase in demands made it impossible to provide adequate pressures through the existing distribution system. As a temporary relief, a special high-pressure electrically driven centrifugal pump was installed in Herron Hill pumping station (which at that time was steam driven) for direct pumpage into the higher parts of Squirrel Hill district. This pump was operated only during periods of heavy water demands, and resulted in fair increase of distribution pressures. A thorough economic study later resulted in the construction of the electrically operated Saline pumping station, to p mp directly into the 3 segregated high areas of the Squirrel Hill district which had previously suffered from shortage of water and inadequate pressures.

This segregated Saline system is connected to the Herron Hill service in such a manner that excess pressure, due to low demands, in the Saline service, is relieved through an automatic valve to the Herron Hill service. In case of an extended power outage at Saline station, for which an adequate and reliable power supply is not economically obtainable at the present time, it is essential that the previously mentioned high pressure unit at Herron Hill station be placed in service so as to maintain the best possible pressures in the districts normally serviced from Saline station.

As Herron Hill station at present is an attended station, the control of Saline station was placed under this operator, who now controls the Saline station over a supervisory control system of the visicode type.

Supervisory Control

For the information of those who are not familiar with supervisory control, it consists of a system of telephone type relays at both Herron Hill and Saline stations connected by 2 telephone wires. The relays are housed in dust-proof, sealed cases which are in turn mounted on steel panels. By the use of such a system, remote apparatus may be selected and operated at will, while lamp indications show the true position of the unit controlled at all times. On the dispatcher's panel at Herron Hill are the control switches and indicating lamps arranged in groups for convenience.

To start the first pump, for instance, a small pushbutton is pressed by the dispatcher. By the use of an automatic relay operation, the Saline relay connected to pump number 1 is selected, which in turn sends a checking signal to the dispatcher. He is informed that the correct selection has been made by the lighting of a small lamp. He then presses the "master control" pushbutton which, through the automatic switching equipment, starts the pump and, after the operation is completed, changes a green lamp indication on his panel to red. The operation is thus completed automatically and the supervisory control equipment resets to normal, ready for any further operation.

Should a motor driven pump, for example, trip out of service, the dispatcher hears an alarm bell. A glance at his board shows him, by another white lamp with black dot, and green position lamp, that the affected pump is out of service. He resets the alarm and starts the same or another pump to take its place.

Thus the dispatcher not only is able to perform the desired operations in the remote station but is kept constantly informed of the operating conditions.

The supervisory control equipment at both stations is mounted on vertical steel panels. The installation work was simplified because the panels came completely wired and tested from the factory. The same was also true of the steel enclosed cubicles which housed the automatic switching equipment for the motor driven pumps. The installation work was thus reduced to setting and anchoring them in place and connecting the main and control cables to their marked terminals. Control panels at Saline station are shown in figure 2.

Advantages of Remote Indication

The safe and successful operation of this station depends, in addition to the conventional control of its 3 pump units, on 3 essential indications: (1) presence of adequate suction pressure, shown by lamp indication on dispatcher's panel; (2) presence of voltage for each of the 3 phases of the 4 kv supply at Saline station, shown on a triplex voltmeter on the dispatcher's panel (this voltmeter is energized from the battery and only records absence or presence of the a-c voltage); finally (3) continuous indication on the dispatcher's panel of the discharge pressure at Saline pumping station, transmitted by 60 cycle impulses over the supervisory control circuit; as the supervisory system is operating by transmittal of d-c impulses, the telemetering operates over the same circuit without interference. The essential purpose of this remote pressure indication is to indicate to the operator at Herron Hill station whether or not the automatic discharge valves at Saline operate properly; in starting a pump unit, the indicating gauge shows static pressure of about 190 pounds; when the automatic discharge valve opens, the gauge must show dynamic pressure, of about 230 pounds. A lack of increase in pressure indicates a failure in the discharge valve, such as a sticking cone, and the unit is immediately stopped, and the other unit started. Another indication of fault may be obtained by abnormal pressure readings when a pump is operating, an excessively high or low pressure being indicative of faulty operation of the automatic pressure relief valve between the Saline service and the Herron Hill service. Considering the magnitude of forces at play in a water system of even moderate proportions, it is easy to realize the utmost importance of detecting such faulty operations which, if not checked and remedied, might result in destruction of pipe lines and stations and serious interruptions in water supply for sanitary and fire protection purposes.

Results Obtained

The plan of modernization of waterworks stations followed by the city of Pittsburgh has shown very gratifying results, reflected in the reduction of the mechanical division's budget from about $929,000 in 1928 to $602,000 in 1936, a reduction of more than 35 per cent. Approximately $^1/_2$ of this reduction has been accomplished by the change from steam to electric operation in the pumping stations.

It is only during the last few years that supervisory control equipment, especially for the simpler installations where only a small number of units are to be controlled, has reached a stage of production and development where its first cost allows its universal application. Where numerous waterworks plants now employ remote metering and indications from automatically controlled stations, using complicated and often unreliable equipments for transmittal, the realization of the simplicity and reliability of supervisory control of the visual type opens many possibilities for system improvements, using present channels for remote metering as well as complete equipment control.

Remote Metering and Automatic Load Control

Power dispatching on an interconnected electric power system has been simplified and greatly improved by the adoption of a remote metering and automatic load control scheme recently developed. Remote metering at the power dispatching center provides continuous indication of the load on a distant 110-kv interconnection. The equipment also provides automatic control of the load on a hydroelectric generating plant located 160 miles from the metering point. The scheme, operating over company owned telephone lines, is based upon maintaining a constant beat frequency in the receiving apparatus, the transmission frequency being varied. Maintenance cost of the equipment is found to be negligible.

By
J. T. LOGAN
ASSOCIATE A.I.E.E.

Georgia Power Company, Atlanta

MANY of the methods employed today in dispatching and controlling loads on electric power systems are those developed years ago, largely under isolated operation. The art of dispatching has lagged other phases of the electrical business principally because too few engineers are familiar with the details of the problems involved. The few engineers who have actually performed the duties of a load dispatcher were too eager to conquer the more technical problems after graduating from the dispatching ranks; consequently the dispatcher must still rely largely upon the telephone. Telephones will probably always have an important place in dispatching; however, interconnections have rendered their use inadequate for controlling important tie line and generating station loads. The time element is too great.

Before the Georgia Power Company's system became a part of a large interconnected system, remote metering and automatic load control were regarded as refinements not absolutely essential to its operation. The problem changed materially, however, for when

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operating as a part of an interconnected system, synchronism is maintained between about 750,000 kw in generating capacity south of Tennessee and a much greater capacity to the north of Georgia through one 110 kv interconnection with Tennessee Electric Power Company. (See figure 1.) To maintain even an approximate load schedule on this line when in parallel with the system to the north required almost continuous use of the telephones; even then the load would frequently get beyond control during load change periods. Figure 2 shows a typical case. The tie line was being used largely to maintain synchronism between 2 large generating centers, and its load carrying ability on definite schedules was limited. A problem which the old methods of dispatching could not cope with was being confronted. After very careful study remote metering and automatic load control were decided upon as offering the real solution.

Development of Suitable Equipment Necessary

The southern terminus of the interconnection with the Tennessee Electric Power Company is at Lindale, Georgia, 70 miles from the dispatching office in Atlanta and 160 miles from the nearest hydroelectric plant (Tugalo) that could be used for load regulating purposes. It was decided to employ company owned telephone lines, which are carried on the same towers with the high voltage power lines, as the transmitting medium for remote metering and automatic load control.

After investigating the characteristics of a number of remote metering schemes suitable for measuring a-c energy, it was discovered that satisfactory equipment for use over low quality telephone circuits or over the power lines themselves was not available. Practically all the developments in this field had been made to satisfy metropolitan problems where distances are relatively short.

The problem faced was one of developing a system of remote metering only, as once given the load indication in the dispatcher's office no difficulty was anticipated in adapting standard apparatus for control of the generators. Before beginning work in the laboratory a set of specifications was agreed which were briefly as follows:

1. The instrument for the dispatcher's office must be of the graphic type. Occasional readings taken from indicating instruments are of little help to a busy load dispatcher. He is more interested in the load drifts as shown by a chart.

2. The signal or translating medium must be continuous, for the reason that impulse methods of transmitting signal current imposes a severe duty upon relays and their contacts, thereby impairing the reliability of the metering system and increasing the maintenance cost.

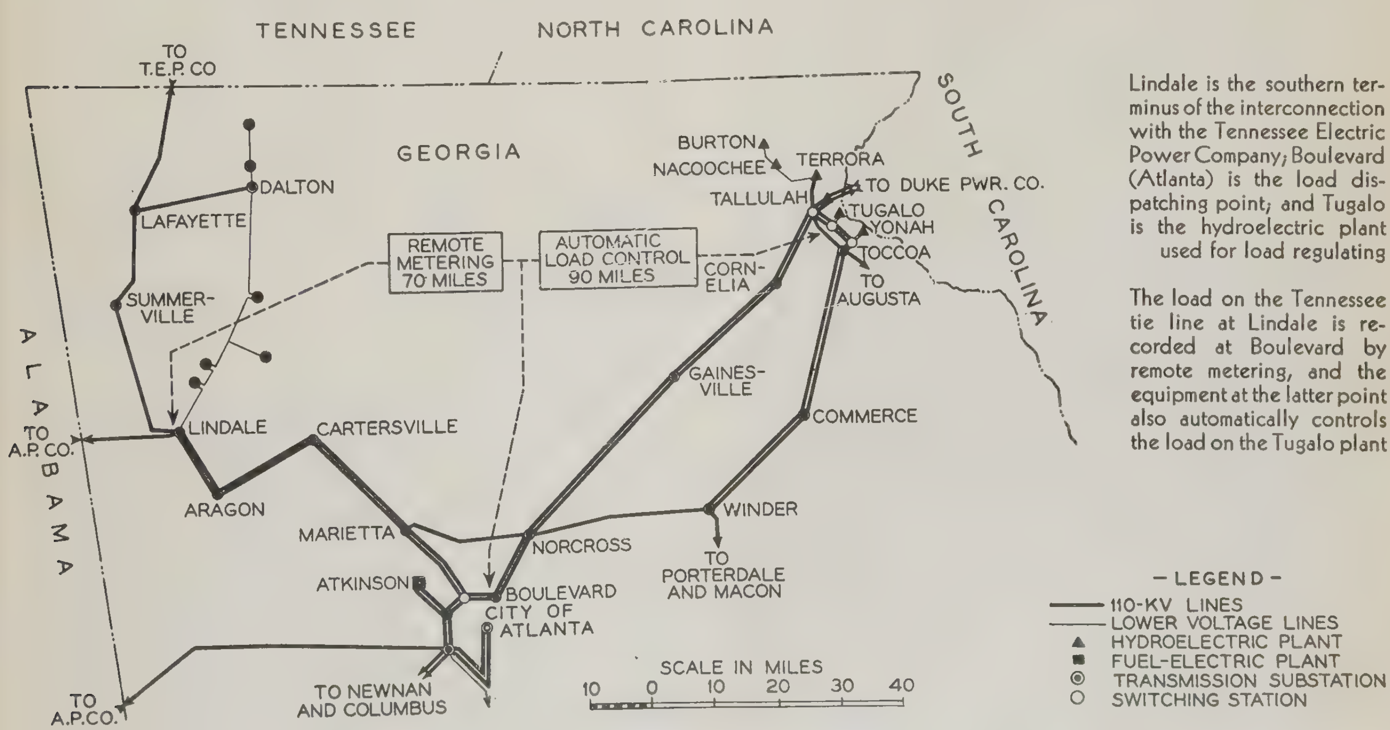
3. The scheme of transmission should be suitable for use over power circuits or telephone circuits subject to induction from 60 cycle power. No other types of company owned circuits were available. Incidentally, this precluded the use of low frequency or direct current as a translating medium, and eliminated most of the schemes already available.

4. The signal transmitted must not interfere with telephone conversations or existing ringing facilities. This meant the use of a frequency above the audible range as a translating medium.

5. The receiver must be capable of accurate reproduction under conditions of varying signal energy. Transmission of constant signal energy over the circuits available could not be accomplished.

6. The apparatus must respond quickly in order to give the dispatcher a true picture of conditions at all times.

With these specifications as an objective, a simple, reliable, and economical system of remote metering, which may be applied to circuits of any reasonable length, has been developed. It is particularly adaptable for electrical measurements, but may also be



Lindale is the southern terminus of the interconnection with the Tennessee Electric Power Company; Boulevard (Atlanta) is the load dispatching point; and Tugalo is the hydroelectric plant used for load regulating

The load on the Tennessee tie line at Lindale is recorded at Boulevard by remote metering, and the equipment at the latter point also automatically controls the load on the Tugalo plant

Fig. 1. Map of a section of the transmission and generating system of the Georgia Power Company showing locations of remote metering and automatic load control equipment

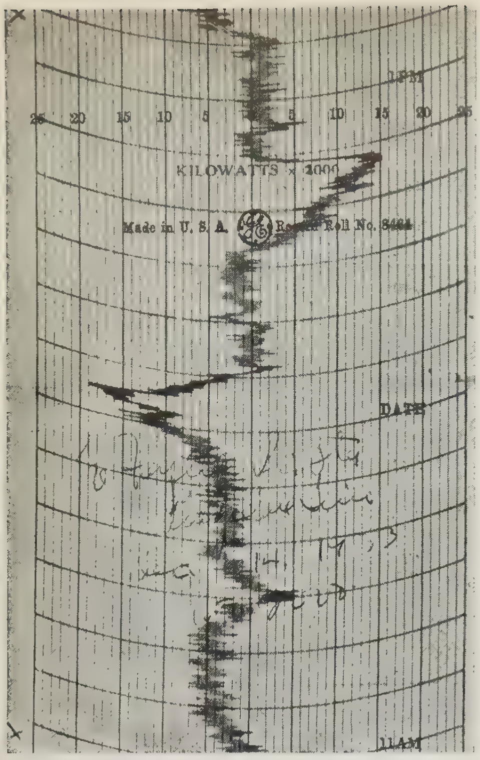


Fig. 2. Section of wattmeter chart showing load drifts during system load change period. This record of load on the Georgia - Tennessee 110 kv tie line was made prior to installing remote metering and automatic load control

Each heavy vertical line represents 5 units, or, since chart constant is 2,000, represents 10,000 kw

Each curved horizontal line represents 10 minutes

The period covered is 11 a.m. until after 1 p.m.

used for obtaining remote readings of temperature, pressure, velocity, position, etc.

Transmitting Equipment

The transmitting equipment consists of a very stable master oscillator; a standard graphic wattmeter modified to actuate a variable condenser for controlling the frequency of the master oscillator; 3 stages of amplification; and a suitable rectifier and filter for supplying the required d-c voltages, thus eliminating the need of batteries. Views of the transmitter are shown in figure 3.

The tuning condenser, actuated by the shaft of the wattmeter, is connected in the oscillator tuning circuit. As the wattmeter shaft changes position the capacitance of the tuning condenser is changed, thus changing the frequency of the oscillator. For every position of the wattmeter shaft the tuning condenser has a different capacitance, consequently the master oscillator generates a different frequency. This arrangement causes the master oscillator to generate a frequency definitely related to the load as recorded by the wattmeter.

The wattmeter is calibrated to eliminate any errors due to adapting the tuning condenser to its shaft. The scale of the meter is 60,000–0–60,000 kw.

Telephone Lines Used as Transmission Circuit

The transmitter frequency is placed on the company's telephone lines, which are subjected to severe 60 cycle induction, through 7-kv 0.005-microfarad condensers. As previously stated, the circuit is 70 miles in length and is continuous from Lindale to the dispatcher's office in Atlanta. Induction is so severe that 15 kva transformers are used at each telephone station as drainage coils. There are normally 8 drainage coils connected to the main trunk circuit.

The high frequency is taken off the telephone lines at the dispatcher's office in Atlanta through condensers similar to those used at Lindale.

Receiving Equipment

The equipment described up to this point does not embody many radically new ideas other than the application of carrier frequencies to remote metering. Remote metering employing variable low frequency transmission had been attempted even as far back as 1924; however, its impracticability is verified by the fact that the equipment has not been placed on the market for general use.

The specifications required that the receiver must not be susceptible to signal energy variations. This exacting requirement was based upon previous experience with carrier current telephone transmission over similar circuits. The energy transmitted may vary to a great extent from day to day. The power for operating the receiving meter must be generated locally. After taking the signal frequency from the telephone lines through condensers, it is passed through a high-pass filter in order to trap out the voice frequencies and the 60 cycle induction and harmonics thereof.

From the high-pass filter, the signal is impressed upon a heterodyne receiver. Heterodyne reception provides for combining the signal frequency with a frequency generated by an oscillator in the receiver to produce a beat frequency. The beat frequency employed is the difference between the signal and oscillator frequencies. The oscillator which is a part of the heterodyne receiver is of a similar type to the one employed in the transmitter, and also is very stable.

This system of remote metering differs from other variable frequency schemes in that it is based upon maintaining a *definite* or *constant beat frequency*. A definite beat frequency can be maintained only by changing the frequency of the receiver oscillator to correspond with changes in the signal frequency. Obviously, this requires a means for automatically operating a tuning condenser for controlling the frequency of the receiver beat oscillator.

This tuning condenser, being matched with the tuning condenser of the transmitter, varies the frequency of the receiver oscillator by an amount corresponding to that of the transmitter for equal movements of the rotor plates.

By equipping the shaft, which actuates the rotor plates of the receiver beat oscillator tuning condenser, with an inking pen and by providing a chart mechanism, a means of reproducing the kilowatt load of the transmitting wattmeter is obtained, provided that a definite beat frequency is maintained. Of course, the receiving wattmeter chart has a scale which is calibrated to correspond with that of the

transmitting wattmeter. In reality, the reverse was done, i. e., a standard graphic wattmeter was stripped of its motivating elements, the tuning condenser adapted to its shaft and a disk type reversible motor provided for driving the shaft.

Maintaining a Definite Beat Frequency

A definite beat frequency may be maintained by causing the motor to rotate the shaft of the receiver tuning condenser in the proper direction for restoring the desired beat frequency any time it varies therefrom. The equipment necessary to accomplish this and its reaction to changes in beat frequency can best be understood by referring to figure 4, parts *A*, *B*, and *C*.

The conditions shown in table I are assumed to prevail.

The beat frequency of 5 kilocycles from the heterodyne receiver is passed through a low-pass filter in order that the signal frequency, which may vary from 42 to 46 kilocycles, and the frequency generated by the oscillator of the receiver, 37 to 41 kilocycles (this could be 47 to 51 kilocycles if desired), will be trapped out of the very sensitive network. From the low-pass filter the beat frequency is amplified through a final power stage of amplification to supply ample power to the network.

Table I—Assumed Conditions

Transmitter Wattmeter Reading	Frequency Generated: Transmitter Oscillator	Receiver Oscillator	Beat Frequency
60,000 kw—incoming (full scale)	42 kc	37 kc	5 kc
0 kw (center scale)	44 kc	39 kc	5 kc
60,000 kw—outgoing (full scale)	46 kc	41 kc	5 kc

The amplified beat frequency is then applied to a network constructed of reactances and capacitances as shown by 14, figure 4(*B*). This network provides that at 5 kilocycles the potential drops around elements 14*a* and 14*b* are equal. These potentials are applied to the grids of the 2 vacuum tubes 15 and 16. The plate circuits of these tubes are differentially connected through a 3-winding transformer, 19.

With the network balanced, 5 kilocycles applied, the grid voltages of 15 and 16 are equal, consequently equal currents flow in the 2 plate circuits. The flux due to these currents cancels out in the transformer core, therefore no voltage is generated in the secondary winding 19*c*. This means that disk 10*a* in the recording meter has no torque applied, as current is not flowing in coil 10*c*. (Coil 10*d* is continuously energized, but produces no torque unless aided by coil 10*c*; it is simply a watt-hour meter assembly.)

Figure 4(*C*) shows the characteristic curves of tubes 15 and 16. Under balanced condition of network 14, tubes 15 and 16 are operating on point *AA'* of characteristic curve *X*. Grid bias battery 17 fixes this point. If the network 14 becomes momentarily unbalanced by a change in the frequency of the received signal the tube operation slides up or down curve *X*, depending upon whether the change is plus or minus, the operation of one tube being in one direction and the other in the opposite direction. This action unbalances the currents in the plate circuits, thus giving a resultant flux in the core of 19 which generates a potential in 19*c*. Coil 10*c* is then supplied with current and disk 10*a* rotates, moving inking pen 10*e* and tuning condenser 9. This operation changes the frequency of the oscillator in the receiver, bringing its frequency to within 5 kilocycles of the signal frequency. At this point the network is again balanced, current no longer flows in 10*c*, and disk 10*a* ceases to rotate until the 5 kilocycle beat frequency is again changed.

Examples of Operation

The operation is further clarified by assuming 2 values of load. Refer again to figure 4.

Zero Load. (Both meters 3 and 10 indicate zero at start.) Meter 3 indicates zero load. Tuning condenser 2 causes oscillator 1 to generate 44 kilocycles which is amplified and placed on the telephone lines through coupling condensers 4. This signal fre-

Fig. 3. Front and rear views of the transmitter

The master oscillator control condenser can be seen located in the lower left corner of the wattmeter case. The grill cover has been removed from the back of the steel cabinet in order to show the general arrangement of the equipment. The cabinet includes a suitable rectifier and filter for supplying d-c voltage, a master oscillator, and 3 stages of amplification

quency is taken off the telephone lines at the receiving station through coupling condenser 6 and passed through high-pass filter 7. The oscillator in 8 generates 39 kilocycles which is combined with the signal frequency for producing a beat frequency. The beat frequency of 5 kilocycles (44 kilocycles − 39 kilocycles) is passed through low-pass filter 12 and amplified by 13, and applied to network 14. Potential drops across 14*a* and 14*b* are equal, therefore the grid potentials of 15 and 16 are equal (network adjusted for balance at 5 kilocycles). The plate currents of 15 and 16 are equal and cancel out in transformer 19. [Tubes operating on AA' figure 4 (C).] No potential is generated in 19*c*, therefore disk 10*a* remains unchanged and inking pen or pointer 10*e* shows zero on chart or scale.

Full Load. (Assuming change from zero to full load outgoing.) Meter 3 moves to full scale deflection and in doing so rotates condenser rotor 2. This change in condenser capacitance causes oscillator 1 to generate 46 kilocycles. The oscillator in 8 is generating 39 kilocycles (from above example). This produces a beat frequency of 7 kilocycles which is applied to network 14. This beat frequency unbalances grid potentials causing tube 15 to operate on, say, BB', figure 2(C) and tube 16 to operate on CC'. The plate current from 16 now predominates in transformer 19, thereby causing a resulting potential to be generated in 19*c*, whose phase relation is controlled by winding 19*b*. The potential from 19*c* causes disk 10*a* to rotate (coil 10*d* is continuously energized). Disk 10*a* continues to rotate until condenser 9 has had its capacitance changed sufficiently to cause the oscillator in 8 to generate 41 kilocycles. At this point the network again becomes balanced at 5 kilocycles (46 kilocycles − 41 kilocycles) and potential or current in 19*c* disappears. The disk 10*a* stops rotating and inking pen or indicator 10*e* shows full scale deflection.

When the load on the circuit at the transmitting station drops, causing the frequency of oscillator 1 to decrease, the reverse occurs in network 14, causing disk 10*a* to rotate in the reverse direction.

The response of the receiving equipment is exceedingly fast. It responds to variations of frequency in the oscillator 1 of 10 cycles or less. After several months of actual operation it is found that the system is very stable. Calibrating adjustments can be made by station operators by means of a small vernier condenser in parallel with condenser 9; however, little or no adjustment has been necessary to date. Once calibrated at zero load the meters track throughout their scales due to matched oscillator control condensers.

Accuracy

This installation of remote metering has been inspected by engineers of some 40 or 50 power systems, the majority of whom have been impressed by its simplicity, performance, and general appearance. A few, however, have questioned its accuracy because of the use of beat frequency. They feel that frequency variations due to instability of the 2 oscillators may become cumulative and if so will reflect a large percentage error in the beat frequency, and consequently in the accuracy of the receiving instrument. For those who question the stability of an oscillator, they are referred to an article by J. B. Dow (see reference 1 at end of paper). Quoting Mr. Dow:

"This is substantially the experimental results shown in curve III in figure 8 wherein a change in frequency of only 10 cycles in 4,500,000 occurs for a 25 per cent change in the common anode voltage supply."

"It has been found that variation in filament voltage has practically a negligible effect upon frequency so long as the filament temperature is maintained above that required for saturation at the anode voltage used."

"Without temperature control of the frequency determining portion of the circuit or tube, a frequency drift of 0.005 per cent per degree change in ambient temperature may be expected."

Such accuracy is almost inconceivable to power system engineers, yet experience with this remote

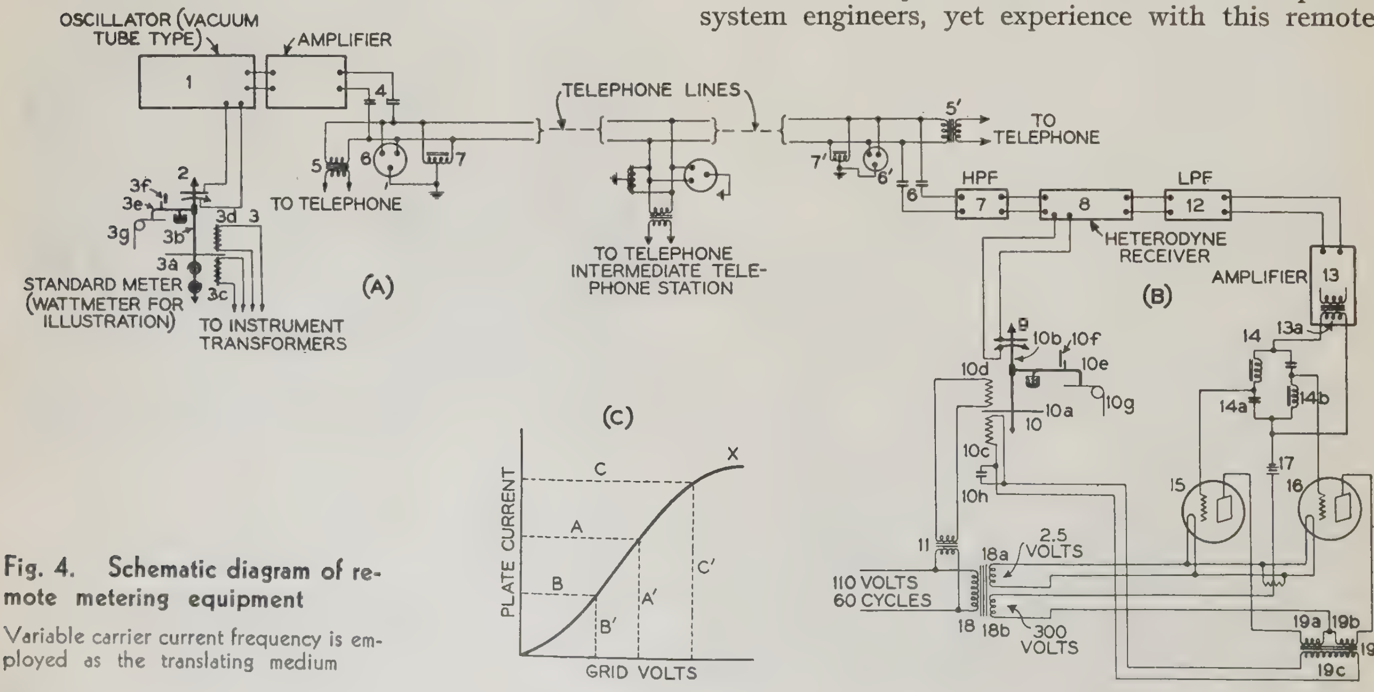


Fig. 4. Schematic diagram of remote metering equipment

Variable carrier current frequency is employed as the translating medium

Fig. 5. Load charts recorded by remote metering equipment

On charts 1 and 3, each heavy vertical line represents 4,000 units, or, since chart constant is 5, represents 20,000 kw. Each horizontal line represents 10 minutes

On charts 2 and 4, each heavy vertical line represents 5,000 units, or, since chart constant is 1, represents 5,000 kw. Each curved horizontal line represents 10 minutes

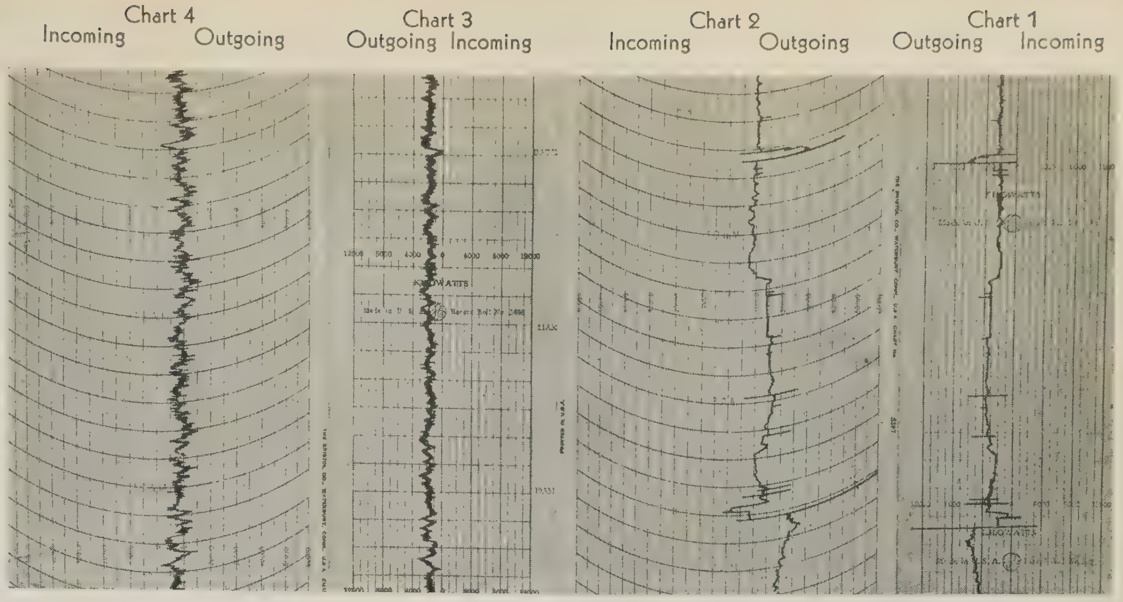


Chart 1—Recorded by the transmitting wattmeter (meter shown in figure 3). Record made during a severe electrical storm, showing load shifts and power surges due to relaying of other important power lines. The Alabama, Georgia, and Tennessee power systems were separated from the "northern systems"

Chart 2—A reproduction of chart 1, recorded in the dispatcher's office 70 miles away. The receiving meter records in the reverse direction to the transmitting meter. These charts are shown to give an idea of the speed of response obtained in this system of remote metering

Chart 3—Recorded by the transmitting wattmeter under normal operating conditions when in parallel with the "northern systems"

Chart 4—A reproduction of chart 3, recorded in the dispatcher's office

metering installation indicates less than 0.1 per cent drifting in the oscillator frequencies. This is verified by an examination of charts, figure 5, where a change in load of 1,000 kw changes the transmitting oscillator frequency only about $33^1/_3$ cycles (transmitting band, 42 to 46 kc). The receiving meter is responding to less than 1,000 kw load changes.

Another criticism of this system of remote metering has been that a frequency band rather than a single sharply tuned frequency is employed, thus limiting the number of channels over one transmitting circuit. This system uses only a 4 kilocycle band and this can probably be reduced. Carrier current telephone transmission, including side bands, employs a band spread of about 10 kilocycles. It is felt that a 10 kilocycle separation between bands is all that is necessary for this system of remote metering; therefore, the number of channels available over any one circuit seems to be ample.

Automatic Tie Line Load Control Is Provided

The recording instrument located in the dispatcher's office has a great deal more torque than is needed for actuating the inking pen and tuning condenser; therefore, this meter was equipped with a set of single-pole double-throw contacts. The movable contact is carried by the meter shaft while the stationary contacts, one on either side of the movable contact, are adjustable. The stationary contacts have bellows spring mountings in order not to interfere with the accuracy of the meter.

The purpose of these contacts is to control a vacuum tube oscillator designed to transmit on either of 2 frequencies. The contacts are designed "raise" and "lower." When either contact is made, its corresponding auxiliary relay operates, inserting the proper capacitance in the oscillator tuning circuit and closing the plate circuit so that a definite frequency is applied to the transmitting circuit. For sake of clarity, assume that when the "raise" makes contact, a frequency of 70 kilocycles is generated, while the "lower" contact closing causes 30 kilocycles to be generated. In series with the common or floating contact of the meter there is inserted a cam type contact making device. This device is motor driven and makes contact for a predetermined time on each revolution of the cam. This is necessary in order to prevent over-regulation. In other words, the generator turbine gates can be moved only a definite amount for each revolution of the cam, and then only if one set of the contacts are made.

The frequency impulses are placed on a telephone line, similar to the one used for remote metering and 90 miles in length, through coupling condensers rated 7 kv, 0.007 microfarad. At the Tugalo hydroelectric plant in Northeast Georgia (see figure 1) the impulses are taken off through coupling condensers similar to those used at the sending end.

Two vacuum tube relays are installed at Tugalo, one tuned to operate on 70 kilocycles and the other on 30 kilocycles. These relays operate auxiliary relays which supply potential for operating the governors of 2 12,500 kw generators. The circuits from the auxiliary relays simply parallel those of the governor push-pull control switch.

The following explanation may clarify any points not already brought out: assume the load schedule on the Georgia-Tennessee tie line calls for 30,000 kw outgoing to Tennessee. The dispatcher adjusts the "raise" contact to indicate 28,000 kw on the meter scale. (The adjustable contacts indicate their posi-

tion on the meter scale.) The "lower" contact is set on 32,000 kw.

As long as the load remains in this band the oscillator is inactive; only the tube filaments are heated, consequently the generators maintain whatever loads they have. Now suppose the load drifts below 28,000 kw. The "raise" contact is made and for each revolution of the antihunting cam an impulse of 70 kilocycles is sent out. The relay at Tugalo tuned for this frequency closes for the duration of the impulse (which is adjustable) and through its auxiliary relay causes the generator loading to increase. It does what the operator would do manually if he were looking at the tie line wattmeter, except much quicker. This process is repeated on the next revolution of the antihunting cam provided the "raise" contact is still closed. When sufficient load has been picked up the "raise" contact on the meter at the dispatcher's office opens and further changes cease until the load again drifts out of the permissible band.

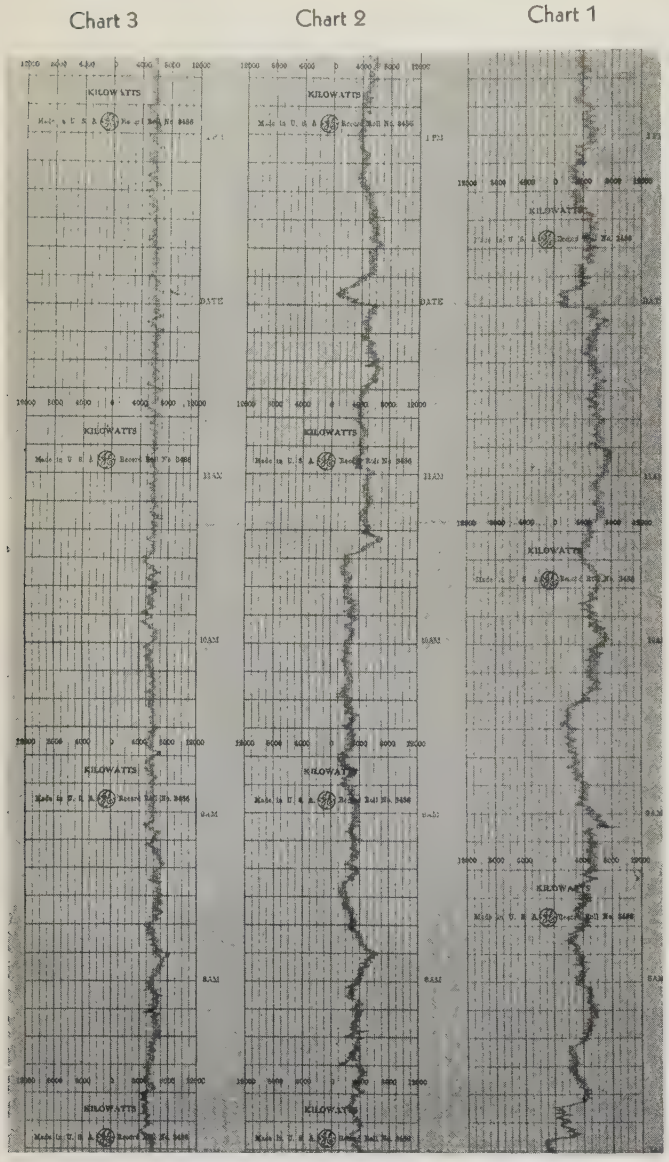


Fig. 6. Charts showing load on the Georgia-Tennessee 110 kv tie line

Chart 1—Chart showing better than average load control by use of telephones. Made prior to installing remote metering on this line

Chart 2—Chart showing the improvements made by providing the dispatchers with remote metering on this line. The dispatchers still had to telephone the various plants for obtaining corrections. Telephone calls between the dispatcher's office and the tie line terminal at Lindale, however, were eliminated

Chart 3—Chart showing the effects of automatic tie line load control. There is evidence of over-regulating; however, this is being eliminated by changes in governor mechanisms. The generators used for load regulation purposes are located 160 miles from the tie line terminus

Each heavy vertical line represents 4,000 units, or, since chart constant is 5, represents 20,000 kw

Each vertical line represents 10 minutes

The period covered is from 7 a.m. until after 1 p.m.

If the load increases above 32,000 kw the operation is reversed, i. e., the "lower" contact comes into play and 30 kilocycle impulses are sent out, causing the relay at Tugalo tuned for 30 kilocycles to operate and reduce the generator loading.

This equipment is very simple, requiring only 3 vacuum tubes at the sending end and 2 at the receiving end. Except for occasional relay contact trouble, which is to be expected in any impulse system, the performance has been entirely satisfactory.

Results

This remote metering and automatic load control equipment has surpassed all expectations. Releasing the telephone lines for other use has more than paid for the installation. More than 200 telephone calls daily have been eliminated between the dispatcher and the Lindale substation operator, and a like number between the dispatcher's office and various generating plants.

The reliable capacity of the Georgia-Tennessee 110 kv tie line has been increased by at least 50 per cent. Schedules of 45,000 kw over this line are now made with less hesitancy than a 30,000 kw load was previously scheduled, and interruptions from load drifts have been practically eliminated. The ability to transmit energy over this line without interruptions, based upon a careful study of load charts, is as shown in table II.

Table II—Loads Which Can Be Carried on Tie Line Without Interruptions

Type Load Control	Load Schedule	(a) Schedule Exceeded by	(b) Relay Setting	(c) Spare Capacity	(d) Safe Load Schedule
1. Telephone only	30,000 kw	25,000 kw	60,000 kw	5,000 kw	30,000 kw
2. Remote metering only	30,000 kw	15,000 kw	60,000 kw	15,000 kw	40,000 kw
3. Remote metering and automatic load control	30,000 kw	5,000 kw	60,000 kw	25,000 kw	50,000 kw

(*a*) The amount the load schedule was exceeded by load drifts some time during the 24 hour period.
(*b*) The relay settings are actually 70,000 kva. At the prevailing power factor, however, this is about 60,000 kw.
(*c*) Capacity which if exceeded will result in overload relays operating.
(*d*) This schedule provides a safety factor of 5,000 kw. While 50,000 kw could be scheduled under 3, it is not considered good economy to schedule above 45,000 kw, except in special cases.

The charts, figure 6, do not show the full benefits accruing from remote metering and automatic load control. This is because the chart made under telephone control (chart 1) is better than the average. Load drifts of the magnitude of those shown by figure 2 were apt to occur during any load change period, thus resulting in interrupting the circuit even under scheduled loads of 30,000 kw. Chart 3 of figure 6, while good, does not show the close regulation now obtainable, as a result of making improvements in the turbine governing system. These improvements eliminate "creeping" of the turbine gates, such as is experienced with flyball governors, and consequently avoid the sawtooth effect noticeable in chart 3 of figure 6.

After about 9 months' experience with this equipment, maintenance cost is found to be negligible.

Remote metering on all tie lines will be provided as required and the practice gradually extended to include important generating plants. This system of metering is ideally adaptable to totalizing. Experiments indicate that the number of circuits that can be combined or totalized on one meter is practically unlimited. To totalize the quantities measured by, say 50 individual meters if all at one location, does not appear at all impractical and the expense would be only slightly more than totalizing the quantities measured by 2 or 3 individual meters.

Reference

1. A Recent Development in Vacuum Tube Oscillator Circuits, J. B. Dow. I.R.E. *Proc.*, v. 19, Dec. 1931, p. 2095–2108.

Distribution Transformer Lightning Protection Practices

By L. G. SMITH
FELLOW A.I.E.E.
Consolidated Gas, Electric Light & Power Co., Baltimore, Md.

With the object of determining the effectiveness of the newer methods of protecting distribution transformers from lightning, a survey of operating data obtained during 1934 by 38 electric power companies has been made by the transmission and distribution committee of the Edison Electric Institute. The results of this survey are presented herewith. In general, interconnection of the lightning arrester ground with the secondary neutral has been found superior to other methods of protection.

In recent years various methods of protecting distribution transformers have been devised with the object of reducing transformer failures and blowing of primary fuses during lightning storms. To obtain operating data on these newer methods in comparison with the conventional method of protecting distribution transformers, a survey was made by the transmission and distribution committee of the Edison Electric Institute. This consisted of collecting operating data for the year 1934. It is planned to continue the collection of these data. At the present time similar data are being collected for the year 1935.

A paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 28–31, 1936. Manuscript submitted Oct. 17, 1935; released for publication Nov. 23, 1935.

On the basis of data collected in 1934, the following conclusions appear to be justified:

1. Interconnection seems to be superior to other methods of lightning protection of distribution transformers.
2. The use of the common neutral system as a means of generally obtaining low ground resistance for interconnection appears promising.
3. Low ground resistance is believed to be one of the most important factors in improving lightning protection.
4. Interconnection does not seem to increase the duty on lightning arresters or their rate of failure.

Various Methods of Lightning Protection

Figures 1 to 5 illustrate the various methods used in the lightning protection of distribution transformers. The interconnection system, shown in figure 2, which nominally consists of a solid tie between the lightning arrester ground and the secondary neutral, may be modified by the insertion of gap *A;* by a gap (*B*) tying the ground to the case; or by a combination in which both gaps *A* and *B* are used. It is interesting to note that 34 out of 38 companies from which operating data have been obtained are using interconnection to some extent.

Results—1934 Lightning Season

Operating data for the 1934 lightning season from 38 companies have been summarized in table I. The data have been combined in an attempt to obtain totals that would tend to eliminate the effect of uncontrolled variables. The combined data are included in table II. It may be noted that the ground resistance is a variable for which compensation can-

Table I—Summary of Operating Data for 1934 for Various Meth

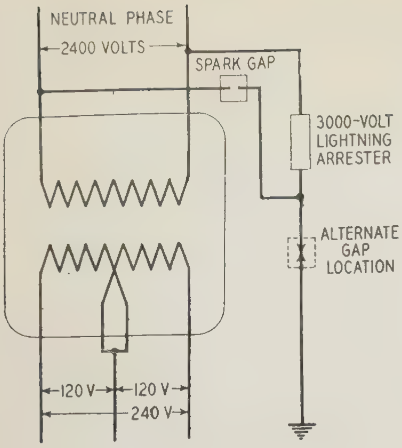
Company	1	2	3	4		5	6			7	
Interconnection											
Solid or gap used?	Used scheme, but no data available	Solid	Solid	Solid	Gap	Solid	Solid	Gap		Solid	
Number of installations		3,708	[b]	537	521	10,000[c]	4,652	646		28	
Type of territory		U.S.		S.	U.S.R.		S.R.	S.R.		R.	
Average ground resistance—ohms		3	1½	25	50	5	5	5		8.7	
Primary fuses blown—per cent		0.94	No data available as yet	18.2	8.25	General improvement noted	1.58	3.13		0.0	
Ratio—change over standard connection—per cent		100.0		198.5	90.0		81.5[d]	161.3		0.0	
Transformer winding failures—per cent		0.135		0.37	0.193		0.161	0.156		0.0	
Ratio—change over standard connection—per cent		69.9		40.2	21.0		80.5[d]	78.0		0.0	
Lightning arrester failures—per cent		0.0		N.D.	N.D.		N.D.	N.D.		3.37	
Ratio—change over standard connection—per cent		0.0								102.13	
Troubles on customer's premises—per cent[a]		0.0		0.4	0.0		N.D.	N.D.		N.D.	
Ratio—change over standard connection—per cent				445.0	0.0						
Meters burned out—per cent[a]		0.323		0.4	0.0		N.D.	N.D.		N.D.	
Ratio—change over standard connection—per cent		83.7		364.0	0.0						
Surgeproof Transformers											
Number of installations	60	None	None	176		34	10			551	
Type of territory	R.			U.S.R.		R.	S.			S.R.	
Average ground resistance—ohms	20.0			125.0 Ω		5.0	250.0			95.6	
Is check made to find gap failures?	No			No		No				Yes	
Primary fuses blown—per cent	0.0			4.55		0.0	No data; installed latter part of 1934			9.78	
Ratio—change over standard connection—per cent	0.0			49.7						91.9	
Transformer winding failures—per cent	0.0			0.0		0.0				0.184	
Ratio—change over standard connection—per cent	0.0			0.0						35.4	
Deion gap failures—per cent	0.0			0.0?		N.D.				1.99	
Ratio—change over standard connection—per cent	0.0			0.0						60.2	
Troubles on customer's premises—per cent[a]	0.0			0.0		0.0				N.D.	
Ratio—change over standard connection—per cent				0.0							
Meters burned out—per cent[a]	0.0			1.14		0.0				N.D.	
Ratio—change over standard connection—per cent				1,036 0							
3 Point Connection											
Number of installations	None	None	None	None		None	None		62		50
Type of territory									R.		R.
Average ground resistance—ohms									80.0		21.0
Primary fuses blown—per cent									11.3		6.0
Ratio—change over standard connection—per cent									106.0		56.3
Transformer winding failures—per cent									0.0		0.0
Ratio—change over standard connection—per cent									0.0		0.0
Lightning arrester failures—per cent									12.8		6.0
Ratio—change over standard connection—per cent									388.0		181.
Troubles on customer's premises—per cent[a]									N.D.		N.D
Ratio—change over standard connection—per cent											
Meters burned out—per cent[a]									N.D.		N.D
Ratio—change over standard connection—per cent											
Standard Connection											
Number of installations	4,150	3,623	5,607	5,222		15,000	516[e]		50[f]	130[g]	18,18
Type of territory	U.S.R.	U.S.R.	U.S.				U.S.		R.	R.	U.S.
Average ground resistance—ohms	15.0	50.0	N.D.	25–200		5–400	250.0		90.0	46	130.
Primary fuses blown—per cent	13.45	0.94	2.14	9.16		N.D.	1.94		10.0	27.7	10.6
Transformer winding failures—per cent	0.29	0.193	0.96	0.92		N.D.	0.20		0.0	0.77	0.52
Lightning arrester failures—per cent	0.60	0.138	N.D.	0.06		N.D.	N.D.		N.D.	N.D.	3.3
Troubles on customer's premises—per cent[a]	0.0	0.0	N.D.	0.09		N.D.	N.D.		N.D.	N.D.	N.D
Meters burned out—per cent[a]	7.08	0.386	N.D.	0.11		N.D.	N.D.		N.D.	N.D.	N.D

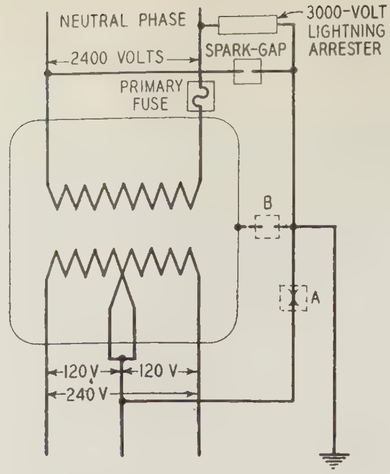
Company	19		20	21	22	23	24	25	26	27	2
Interconnection											
Solid or gap used?	Solid	Gap	Solid	Solid	Solid	Solid					So
Number of installations	144	72	1,300	4,582	A few	1,919	None	None	None	None	43
Type of territory	U.S.R.	R.	U.S.	U.S.R.		U.					U.
Average ground resistance—ohms	30.0	30.0	0.25	9.8	N.D.	1.0					
Primary fuses blown—per cent	5.6	7.2	1.46	0.15	N.D.	0.104					0.
Ratio—change over standard connection—per cent	63.6	81.8	53.1	3.72		9.04					
Transformer winding failures—per cent	2.78	0.0	0.08	0.0	N.D.	0.052					
Ratio—change over standard connection—per cent	264.0	0.0	62.5			∞					
Lightning arrester failures—per cent	1.39	1.39	0.0	0.066	N.D.	0.0					0.
Ratio—change over standard connection—per cent	158.0	158		1.64		0.0					
Troubles on customer's premises—per cent[a]	0.0	0.0	0.0	0.0	N.D.	0.0					0.
Ratio—change over standard connection—per cent											
Meters burned out—per cent[a]	0.0	0.0	0.0	0.0	N.D.	0.0					1.
Ratio—change over standard connection—per cent	0.0	0.0									
Surgeproof Transformers											
Number of installations	29		15	None	50	5	5	8	None	None	N
Type of territory	R.				R.	S.R.	R.	U.S.R.			
Average ground resistance—ohms	43.0				10.0	20.0	20.0	12.0			
Is check made to find gap failures?	No				No	Yes	No	No			
Primary fuses blown—per cent	13.7				0.0	20.0	N.D.	N.D.			
Ratio—change over standard connection—per cent	155.8				N.D.	1,739.0					
Transformer winding failures—per cent	0.0				0.0	0.0	0.0	0.0			
Ratio—change over standard connection—per cent	0.0				0.0						
Deion gap failures—per cent	3.45				0.0?	0.0	0.0?	0.0?			
Ratio—change over standard connection—per cent	392.0				N.D.	0.0					
Troubles on customer's premises—per cent[a]	0.0				0.0	0.0	0.0	0.0			
Ratio—change over standard connection—per cent					N.D.						
Meters burned out—per cent[a]	0.0				N.D.	0.0	0.0	0.0			
Ratio—change over standard connection—per cent	0.0										
3 Point Connection											
Number of installations	None		None	None	100	None	None	20	None	None	N
Type of territory					U.S.R.			U.S.R.			
Average ground resistance—ohms					10.0			12.0			
Primary fuses blown—per cent					N.D.			N.D.			
Ratio—change over standard connection—per cent											
Transformer winding failures—per cent					0.0			0.0			
Ratio—change over standard connection—per cent					0.0						
Lightning arrester failures—per cent					N.D.			0.0			
Ratio—change over standard connection—per cent											
Troubles on customer's premises—per cent[a]					0.0			0.0			
Ratio—change over standard connection—per cent											
Meters burned out—per cent[a]					N.D.			0.0			
Ratio—change over standard connection—per cent											
Standard Connection											
Number of installations	569		4,700	124	1,400	3,481	None	1,500	4,500	14,500	N
Type of territory	U.S.R.		U.S.R.	U.S.R.	U.S.R.	U.S.R.		U.S.R.	U.S.R.	U.S.R.	
Average ground resistance—ohms	30.0		35.0	12.2	10.0	38.0		12.0	80.0	N.D.	
Primary fuses blown—per cent	8.8		2.75	4.03	N.D.	1.15		N.D.	N.D.	N.D.	
Transformer winding failures—per cent	1.05		0.128	0.0	0.714	0.0		N.D.	2.44	0.248	
Lightning arrester failures—per cent	0.88		0.0	4.03	N.D.	0.029		N.D.	N.D.	N.D.	
Troubles on customer's premises—per cent[a]	0.0		0.0	0.0	N.D.	0.0		N.D.	N.D.	N.D.	
Meters burned out—per cent[a]	0.703		0.0	0.0	1.85	0.0		N.D.	N.D.	N.D.	

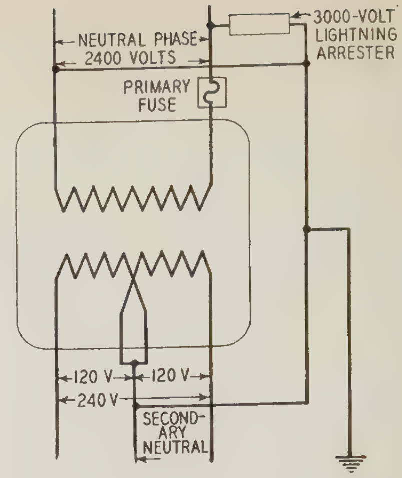
8	9			10	11	12	13	14		15	16		17	18
	Solid													
Gap	Yi	Δi	Total	Solid	Solid	Solid	Solid	Solid	Gap	Solid	Solid	Gap	Solid	Solid
61	3,575	3,536	7,111	12,000	4,709	3,175	1,934	97	98	4,143	900	600	9	427
R.S.	U	U.S.R		U.S.	U	U.S.	S.R.	R	R	U.S.			U.S.	U
70	10	120		0.5	0.6	1.0	2.0	22.8	101.0	N.D.	25.0	25.0	10.5	3.0
N.D.	6.1	32.3	19.1	0.295	0.064	0.72	0.154	10.3	9.2	0.94	N.D.	N.D.	N.D.	0.47
	22.2	64.2	44.7	26.5			44.1	52.5	47.0	12.0				
N.D.	0.78	1.73	1.25	0.067	0.042	0.22	0.103	1.03	0.0	0.6k	N.D.	N.D.	N.D.	0.7
	26.2	63.9	45.0	47.7			103.0	100.0	0.0	17.3				
N.D.	N.D.	N.D.	N.D.	0.141	0.021	0.22	0.154	1.03	0.0	0.048	N.D.	N.D.	N.D.	0.0
				164.1			102.6	+∞		14.5				
N.D.	N.D.	N.D.	N.D.	N.D.	0.0	0.0	0.0	0.0	0.0	N.D.	0.0	0.0	0.0	0.0
													0.0	
N.D.	N.D.	N.D.	N.D.	N.D.	0.021	0 22	0.0	0.0	0.0	0.37	0.0	0.0	0.0	0.0
													0.0	
3		99		None	None	None	None	11		591	30		12	A few
S.R.								R		S.R.			R	
N.D.		200.0						66.5		N.D.	25.0		10.5	
Yes		Yes						No		No	N.D.		Yes	
N.D.		1.01						9.1		0.34	0.0		16.67	
		2.0						46.4		4.45			487.0	
N.D.		0.0						0.0		1.01	0.0		0.0	
		0.0						0.0		29.2			0.0	
N.D.		16.16						0.0?		3.05?	N.D.		16.67	
										925.0			4,900.0	
N.D.		0.0						0.0		N.D.	0.0		0.0	
													0.0	
N.D.		0.0						0.0		N.D.	N.D.		0.0	
													0.0	
None				None	None	None	None	None		None	None		None	20l
														R
														3.0
														5.0
														5.0
														0.0
														0.0
														0.0
4,000	3,575	7,405	10,980	10,200	None	None	1,992	97		9,287	13,255		6,795	None
U.S.R.				U.S.			S.R.	R		S.R.			U.S.R.	
70.0	50.0	60.0	60.0	14.0			30.0	93.5		N.D.	25.0		19.45	
2.75	27.4	50.3	42.8	1.11			0.35	19.6		7.8	N.D.		3.42	
0.875	2.97	2.71	2.79	0.14			0.1	1.03		3.46k	1.1		0.12	
0.375	N.D.	N.D.	N.D.	0.086			0.15	0.0		0.33	N.D.		0.34	
N.D.	N.D.	N.D.	N.D.	N.D			0.0	0.0		N.D.	0.0		0.015	
2.50	N.D.	N.D.	N.D.	N.D.			0.0	0.0		N.D.	N.D.		0.472	

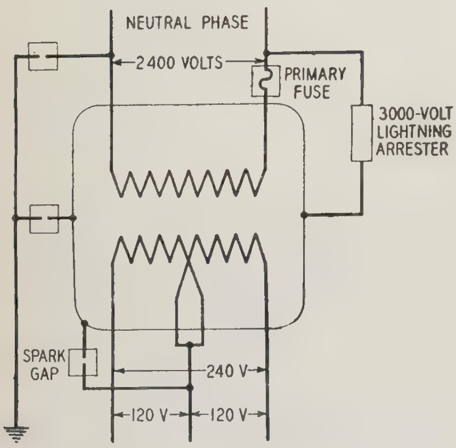
29	30	31	32	33	34		35	36	37	38	Total		
lid	Solid m	Solid	Solid	Solid	Solid	Gap	Gap	Both	Solid	?	Solid	Gapped	Both
	29,760	50	6,851	866	41	57	193	11,122	2,063	202	105,529	1,583	107,112
S.R.	U.S.R.	U	U.S.R.	U	U	U	R	U.S.R.	U	S			
9	10.0	N.D.	1.0	30.0	0.0	0.0	N.D.	N.D.	10.0	15–100	14.4	37.2	18.3
0	2.79n	N.D.	0.51	1.50	4.88	0.0	30.0	2.37	1.02	0.97	2.77	8.72	2.85
0	102.5			11.1	125.3	0.0	53.5	33.9	53.7	19.1	32.7	103.1	33.6
0	0.477	N.D.	0.0875	0.116	0.0	0.0	N.D.	N.D.	0.295	0.330	0.340	0.379	0.341
0	308.0			14.5	0.0	0.0			57.7	31.1	41.3	46.1	41.5
0	2.385n	N.D.	0.614	N.D.	0.0	0.0	N.D.	N.D.	N.D.	N.D.	1.06	0.441	1.06
	110.0										64.1	26.6	64.0
0	N.D.	0.0	0.0	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.			
0													
0	N.D.	0.0	0.146	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.130	0.0	0.127
0										50.0d	10.65	0.0	10.4
	4	None	None	96	14		None	71	None	37		1,994	
R	R			R	U			S.R.		No data available			
D	10.0			N.D.	N.D.			2.0				75.1	
o	No data recorded			No	No								
0				2.085	0.0			0.0				3.77	
0				15.4	0.0			0.0				44.5	
0				0.0	0.0			0.0				0.353	
0				0.0	0.0							42.9	
0?				0.0	0.0			0.0				2.27	
												137.3	
0				0.0	N.D.			0.0					
0													
0				0.0	N.D.			0.0				0.261	
0												21.4	
one	None	None	None	22	None		None	None	None	None		154	
				R									
				N.D.								18.8	
				0.0								7.08	
				0.0								83.6	
				0.0								0.365	
				0.0								44.3	
				0.0								6.32	
												382.0	
				0.0									
				0.0								0.0	
												0.0	
200	16,172	5,380	None	4,366	3,362		51	4,053	3,601	473o		165,914	
S.R.	U	U.S.R.		U.R.	U		R	U.S.R.	U	S.R.			
0.0	15.0	30.0		N.D.	N.D.		N.D.	N.D.	10.0	15–100		62.6	
76	2.72n	2.23		13.52	3.895		56.0	6.99	1.9	5.07		8.46	
385	0.155	0.075		0.801	0.635		N.D.	N.D.	0.511	1.06		0.823	
D	2.17n	N.D.		N.D.	0.0		N.D.	N.D.	N.D.	N.D.		1.653	
25	N.D.	N.D.		N.D.	N.D.		N.D.	N.D.	N.D.	N.D.			
289	N.D.	N.D.		N.D.	N.D.		N.D.	N.D.	N.D.	N.D.		1.22	

a—Percentage based upon number of transformers involved.
b—Being installed 1934.
c—Approximate.
d—As compared with results with standard connection in surrounding area.
e—This includes data on 516 3 phase transformers and is not directly comparable with interconnection.
f—One ground rod salted
g—Ground resistance lowered to 30 ohms.
h—Balance on system.
i—3-phase 4-wire system.
j—Delta system.
k—Includes both bushing and transformer winding failures.
l—On 13.2 kv system.
m—This company reports that the interconnections are in a much more exposed area than the area of the standard connections. The performance of the interconnections constituted a decided improvement over that of the standard connections previously used in the same area.
n—Delta system; lightning arrester failures and primary fuses blown are based upon number of transformers. If based upon number of lightning arresters, divide percentage of lightning arrester failures by 2.
o—3 years.
R—Located in rural sections.
S—Located in suburban sections.
U—Located in urban sections.
N.D.—No data.
By "ratio—change over standard connection" is meant the ratio of performance of one connection to that for the standard connection expressed in per cent.









Figs. 1 to 5. Five methods of protecting distribution transformers from lightning

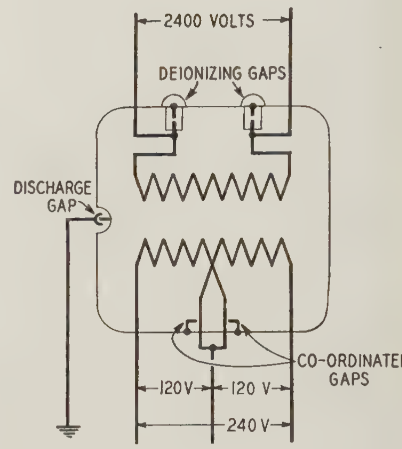
Fig. 1 (upper left). Conventional or standard lightning arrester connection

Fig. 2 (above). Interconnection of arrester ground and secondary neutral

Fig. 3 (upper right). Interconnection obtained by common primary and secondary neutral

Fig. 4 (left). Three point protection

Fig. 5 (right). Surgeproof transformer



not be made. Storm frequency and severity and degree of exposure have been at least partially eliminated as variables by combining the results of various companies. From the average results in table II it is apparent that interconnection shows the best results, surgeproof transformers second, 3 point connection third, and the standard connection last.

An attempt has been made to represent the data graphically, as a function of ground resistance, in figures 6 and 7. This has been done based upon the experience that lowering the ground resistance in itself effects some improvement in the protection rendered. In table III, the results for a 3 year period in 2 sets of test installations made by one company demonstrate this point.

In future studies, an attempt will be made to segregate the data as to location of the primary fuse and to obtain some operating data to determine the effect of various methods of protection upon the locations of transformer winding failures. A study of the effect of the methods of lightning protection upon the location of transformer winding failures seems to be desirable in view of the fact that the data from one company for 4 years of operation show that 38.8 per cent of the winding failures involved the secondary winding only, 33.4 per cent involved both the primary and secondary windings, and 26.2 per cent involved the primary winding only.

Interconnection. Table II indicates that interconnection shows the best operating results. From table I it can be seen that interconnection results in a lower rate of primary fuses blown for 22 companies, the rate being higher for only 2 companies using solid interconnection, 1 company using gapped interconnection, and 1 company using both solid and gapped interconnection. Transformer winding failures were less for interconnection except for 4 companies which showed a higher rate and 2 companies which showed an equal rate. For all companies, the rate of meters burned out is less with interconnection. While these data are favorable to interconnection, a study of figures 6 and 7 indicates that the improvement is attributable in a large measure to lower ground resistance with interconnection, since in making interconnections many companies seek to obtain low ground resistance, which in itself should effect better protection. Therefore, any comparative data should take into account the value of ground resistance. However, it must be considered that the degree of exposure and the storm frequency were variable, and the location of the primary fuse was not considered in tabulating these data.

Surgeproof Transformers. From table II it can be seen that the surgeproof transformers show much better results than transformers with the standard connection, but not quite as good as interconnection. In considering the rate of transformer winding failures, it must be remembered that the transformers

used for surgeproof protection are relatively new.

Another feature of the performance of surgeproof transformers is the higher rate of protective gap failures as compared with lightning arrester failures, particularly when it is considered that several companies reporting do not inspect to determine if the gaps have failed. However, as these data represent several types of gaps, the newer gaps should exhibit much lower rates of failure.

Three Point Protection. The data on 3 point protection represent so few transformer installations that they are believed to be insufficient to justify conclusions.

Lowering Resistance of Arrester Grounds

In view of the importance of ground resistance, a survey has been made of the practice of various companies in maintaining low lightning arrester ground resistance.

Standard Connection. In spite of the fact that evidence indicates the increased protective value of low resistance lightning arrester grounds, of the 33 companies reporting using the standard connection 22 do not salt lightning arrester grounds. Apparently, 3 companies make a practice of salting all arrester grounds, and 7 companies salt them to some extent. One company salts arrester grounds in one district and does not in another. In analyzing the attempt to obtain low resistance arrester grounds it may be noted that 15 companies of the 33 do attempt to reduce the resistance to some specific value. The limit set varies from 10 to 100 ohms, the average being in the neighborhood of 25 ohms. While all arrester grounds are not reduced to the limiting value, usually the average resistance is less than the maximum set. Three companies reduce the arrester ground resistance to a maximum value at locations where trouble has occurred. Fourteen companies set no limit.

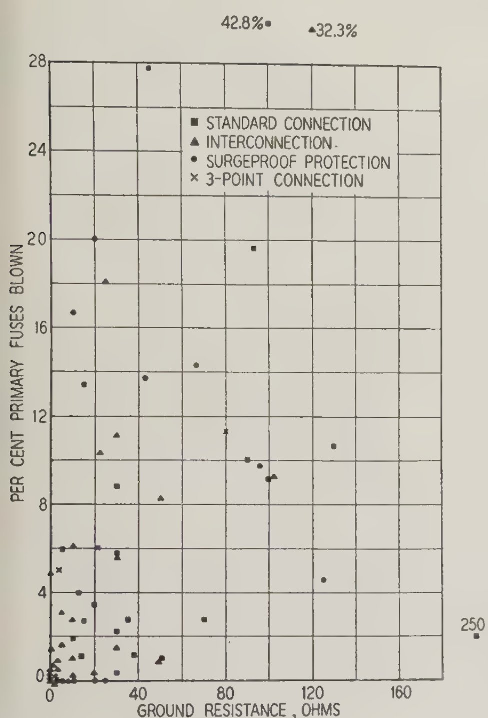


Fig. 6. Effect of ground resistance on primary fuses blown; all types of protection

The data in table III and in figures 6 and 7 indicate a definite trend toward a reduction of primary fuses blown and transformer winding failures with lower arrester ground resistances, indicating the importance of maintaining these resistances at as low a value as practicable.

Interconnection. Because of the solid tie between the lightning arrester ground and the secondary neutral with the interconnection scheme of protection, some engineers believe that the combined ground resistance should be low so that if a lightning arrester should fail sufficient current would flow to cause it to blow clear, trip the feeder, or blow a branch fuse. Of 32 companies using solid interconnection, 12 require water pipe grounds on customers' services before interconnections are made, and 6 set a maximum limit on the combined ground resistance, this limit varying from 1 to 30 ohms. Two companies make interconnections only where a common primary and secondary neutral system is used. Eight companies do not require water pipe grounds and set no limit on the maximum value of combined ground resistance but do set a limit on the minimum number of driven grounds, this limit varying from 2 to 5. Four companies set no restrictions at all on making solid interconnections.

Of the 6 companies using gapped interconnections where information on ground resistance was available, there are no restrictions as to ground resistance

Table II—Combined Operating Data on Various Schemes of Protecting of Distribution Transformers From Lightning

	Standard Connections	All Interconnections	Solid Interconnections†	Gapped Interconnections	Surgeproof Transformers	3 Point Protection
Number of installations	165,914	107,112	105,529	1,583	1,994	154
Average ground resistance, ohms	62.6	18.3	14.4	37.2	75.1	18.8
Primary fuses blown, per cent	8.46	2.85	2.77	8.72	3.77	7.08
Per cent of fuses blown with standard connection		33.7	32.7	103	44.5	83.6
Transformer winding failures, per cent	0.823	0.341	0.340	0.379	0.353	0.365
Per cent of winding failures with standard connection		41.5	41.3	46.0	42.9	44.3
Lightning arrester failures, per cent	1.653	1.06	1.05	0.441	2.27	6.32
Per cent of arrester failures with standard connection		64.1	63.5	26.7	137.3	382
Meters burned out*	1.22	0.128	0.130	0.0	0.261	0.0
Per cent of meters burned out with standard connection		10.5	10.7	0	21.4	0

* Per cent of meters burned out based upon total number of transformers rather than total number of meters. This was necessary as complete data on total number of meters were not available.

† Some common neutral systems are included in data on interconnection.

Note: The combined percentages were obtained by adding the number of cases of trouble for each company for which the data were available. The base for each case was determined by adding the number of transformer installations for each company for which the particular type of trouble data were available. As an example, the percentage of primary fuses blown was determined by adding the fuses blown for each company and taking this total as a percentage of the sum of the number of transformer installations on which data were submitted on primary fuses blown.

Table III—Effect of Ground Resistance on Lightning Protection Rendered Using Standard Connection of Lightning Arresters

	Number of Installations	Primary Fuses Blown	Transformer Winding Failures
Ground resistance not lowered (probably more than 100 ohms)	773	26.0%	1.4%
Ground resistance lowered to 30 ohms or less	130	19.23%	0.733%
Ratio of troubles with lowered ground resistance to those with high ground resistance		73.8%	52.4%

Table IV—Analysis of Use of Common Primary and Secondary Neutral on 3-Phase 4-Wire Primary Distribution Systems

Companies using common neutral entirely or to a large extent	10
Companies using common neutral to a small extent	15
For experimental purposes	8
On all new work	3
Entirely on 3-phase 4-wire primary system where that is part of entire system	4
Companies not using common neutral system	25
Not considering its use in future	15
Planning or considering its use in future	10
Total companies reporting	50

or the number of grounds for making of this type of interconnection.

Surgeproof Transformers. Of the 22 companies using surgeproof transformers from which data are available, only 1 company salts all arrester grounds and 4 salt some of the grounds. The remainder (17) do not salt arrester grounds. However, 7 companies do attempt to hold the arrester ground resistance down to some definite maximum and 3 do this at locations where trouble has occurred. The remaining 12 companies make no such attempt.

Lightning Arrester Failures

A study of tables I and II shows that the rate of failure of lightning arresters is not increased with interconnection, the combined figures in table II indicating a slightly lower rate of failure for interconnection as compared with the standard connection. Since interconnection provides better protection than the standard connection, the conclusion might be reached that the increased duty on the arresters results in a higher rate of arrester failure with interconnection.

While the total figures indicate a lower rate of lightning arrester failure for interconnection, it must be considered that all the comparative data are not from the same companies. Operating data for interconnection and standard connection from the same companies, which should make the data more comparable, show that of 12 companies using solid interconnection the rate of lightning arrester failure is higher for interconnection for 6 of the companies, both rates are the same for 2 companies, and the rate for interconnection is lower for 4 companies. In the 3 cases of gapped interconnection for which comparative data are available from the same company, 1 showed a higher rate of lightning arrester failures for interconnection and 2 showed the same rate for interconnection and standard connection.

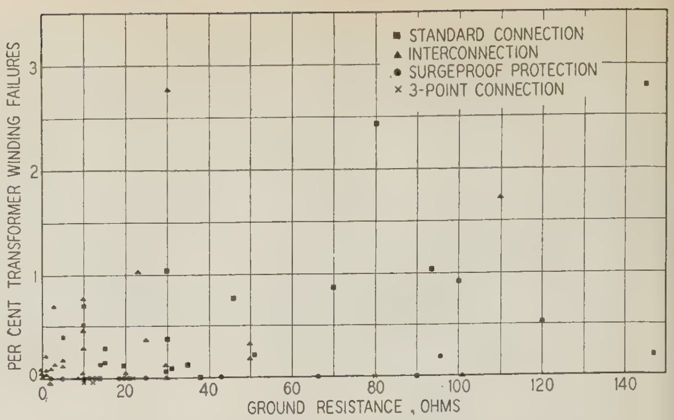


Fig. 7. Effect of ground resistance on transformer winding failures; all types of protection

It was thought that the resistance of the lightning arrester ground might have some effect on the rate of arrester failures, that is, the lower the ground resistance the greater the duty and consequently the higher the rate of failures. Figure 8 shows an attempt to correlate the rate of lightning arrester failure with ground resistance for the standard connection. Except for one point, a falling characteristic is noted, indicating some justification of this theory. However, when similar data are plotted for interconnection, a rising characteristic is shown.

Common Neutral System

The use of a common conductor for the secondary neutral and the neutral of 3-phase 4-wire primary systems has a material bearing upon the lightning protection rendered. With a common neutral system, interconnection may become automatic as

Table V—Use of Supplementary Grounds in Addition to Grounds on Customer's Premises by Companies Using Common Neutral System

Companies not using supplementary grounds	1
Companies using supplementary grounds	24
At each transformer	9
At every fourth or fifth pole	2
At every pole	2
2 grounds on poles adjacent to each transformer	2
Grounds at least every 800 feet	2
Grounds at least every 1,000 feet	3
Grounds driven where less than 2 water pipe grounds exist	2
No schedule of additional grounds prescribed	2
Total	25

Table VI—Analysis of Multiple Grounding of Primary Neutral by Companies Where Common Neutral Is Not Used

Companies not grounding except at supply station	30
Companies using multiple grounds	8
Every 1,500 feet	1
At end of feeders	1
At every industrial service	2
No schedule followed	3
Multiple grounds in only a few cases	1
Total	38

shown in figure 3. The use of a common neutral system is predicated usually upon low ground resistance; hence, no further requirements need be fulfilled in order to meet the limitations upon ground resistance often imposed.

A survey made to determine the prevalence of systems with common neutral yielded the results summarized in table IV. It is significant to note that 35 companies of a total of 50 are either using it altogether or in part, or are planning or considering its use. In view of the fact that if the primary neutral be broken the ground resistance must be maintained low enough to hold the neutral at ground potential, it is the general practice to supplement the grounds on customers' premises by additional grounds made directly on the primary neutral. While the installation of such supplementary grounds may be important where the customer density is low, it is not of such importance where the customer density is high. Table V analyzes the practices of the 25 companies using the common neutral system relative to the installation of supplementary grounds.

Since one of the objections that has been raised to the common neutral system is the effect of multiple grounds on the primary neutral upon telephone interference, an analysis has been made of the practice of companies in making multiple grounds on the primary neutral where the common neutral system is not used. Table VI gives such an analysis. Since some of the companies referred to duplicate some of the 15 companies in table V using the common neutral system on parts of their distribution systems, it is of interest to note that of the 25 companies not using the common neutral system at all, 3 use multiple grounding of the primary neutral entirely and 1 uses it to a limited extent. Thus, there are 29 companies of a total of 50 having multiple grounds on the primary neutrals on all or parts of their distribution systems.

The operating results of lightning protection rendered by this system have been included in data for interconnections in tables I and II where operating data have been received from companies using the common neutral system with interconnection.

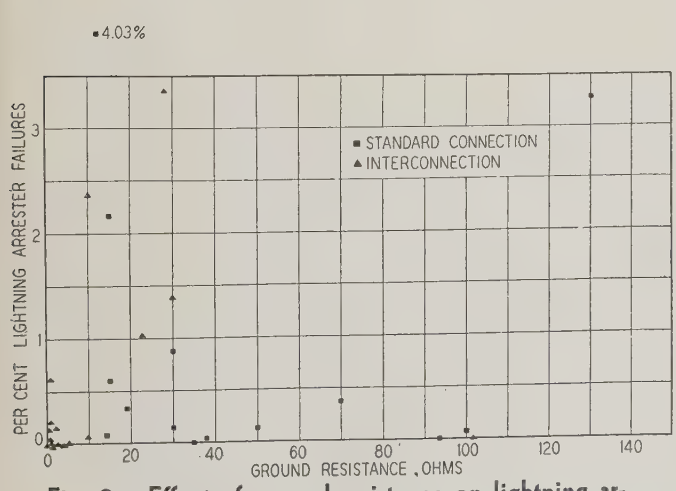


Fig. 8. Effect of ground resistance on lightning arrester failures; interconnection and standard connection

Lightning Protection for Transformers

As part of the modernization symposium scheduled for the 1936 winter convention, the A.I.E.E. transformer and lightning arrester subcommittees* have prepared this joint report, which summarizes briefly methods now available for protecting transformers against both traveling waves and direct strokes.

CONSIDERABLE advance in knowledge with relation to the protection of transformers from the effects of lightning has been made in the last decade. This has been the result of field studies made co-operatively by the 2 largest manufacturing companies and several of the utility companies. The work has been backed up by a large amount of laboratory research with respect to impulse characteristics of the component parts of stations, including insulators, transformers, and protective means and devices. As a result of this better understanding of the underlying principles of protection, changes frequently can be made in protective arrangements which will result in an increased factor of safety. When new installations are made, recognition of these principles of protection will often result, not only in a higher factor of safety against apparatus failure, but frequently in effecting substantial economies.

This discussion will attempt only to present various up-to-date ideas on the protection of transformers. In order that a transformer may be properly protected, it is required that 3 things be known: the magnitude of the overvoltages to which the transformer may be subjected, the insulation strength of the transformer, and the performance of the protective equipment.

Abnormal Voltages and Currents

In addition to overvoltages of ordinary frequencies arising from generator overspeed, there are, in general, 3 types of overvoltages to which apparatus

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*Personnel of A.I.E.E. transformer subcommittee: J. E. Clem, *chairman;* G. M. Armbrust, F. F. Brand, E. S. Bundy, F. A. Lane, A. C. Monteith, L. C. Nichols, J. R. North, H. J. Scholz, E. D. Treanor, and F. J. Vogel.

*Personnel of A.I.E.E. lightning arrester subcommittee: K. B. McEachron, *chairman;* R. H. Earle, I. W. Gross, T. H. Haines, Herman Halperin, C. F. Harding, W. D. Ketchum, J. R. McFarlin, A. M. Opsahl, A. H. Schirmer, H. K. Sels, and H. S. Phelps.

may be subjected, namely, arcing grounds, switching surges, and lightning. Experience indicates that transformers insulated to withstand the present standardized impulse tests will withstand successfully the overvoltages from both arcing grounds and switching surges. Lightning is therefore the most important from a system operation and protection viewpoint. It may be broadly dealt with in 2 limiting classes, traveling waves and direct strokes.

Data obtained during the lightning investigation carried on during the past decade bear out the statement that the maximum voltage which will travel on the transmission line is limited by the flashover of the insulation and is only indirectly related to the circuit voltage. Also, the data indicate that the highest voltages, predominantly negative in polarity, are caused by direct strokes. Although the voltages that have been measured were limited by the insulation flashover, these direct strokes may involve currents from 2,500 amperes to possibly 200,000 amperes. The magnitude of current depends on whether the stroke is a direct hit or a streamer, both of which may have varying magnitudes of energy in them.

Except where wood pole construction is used with ungrounded hardware, the line insulation used on the systems in the United States is roughly proportional to the system voltage, in that the insulation commonly used increases as the system voltage increases. The proportionality is neither uniform nor consistent in the various parts of the country, but it can be expected that the traveling waves of highest voltage will be found on the systems operating at the highest voltages. The severity of the direct stroke and of its resulting current will be practically independent of system voltage. The problem of protecting apparatus on low voltage circuits is therefore relatively more of a problem than on high voltage circuits because wood pole lines are generally used and the cost of the equipment to be protected does not warrant as extensive a protective scheme.

The use of fused gaps is of doubtful value on account of multiple strokes. It has been found that multiple strokes may impose a series of overvoltages on a transmission line or station equipment as close together as a fraction of a cycle or as far apart as 9 to 10 cycles. As many as 12 successive strokes have been recorded and as many as 40 have been photographed. Data indicate that about 20 per cent of the strokes recorded were multiple.

Strength of Transformers

The effect of lightning on transformer insulation depends mainly upon 2 factors, which are the magnitude and duration of the voltage. The impulse test made in accordance with the impulse test code gives a measure of the insulation strength of the transformer under the conditions prescribed by the code. The tests now required are:

(a). Apply a wave just sufficient to cause flashover of the specified test gap under existing conditions of humidity and air density.

(b). Apply a wave sufficient to cause flashover of the bushing (when oversize bushings are used the bushings will be equipped with suitable gaps so as to have the same impulse flashover as the standard bushings). For this test the applied voltage must be at least 5 per cent in excess of the standard minimum flashover of the bushing under standard conditions of humidity and air density.

(c). Apply a wave having a crest not less than 90 per cent of that required to cause flashover of the bushing under existing conditions of humidity and air density. In this test no flashover of the bushing shall occur.

The wave used for testing transformers is the 1.5x40 microsecond positive wave.

The impulse test sets up insulation strengths for the various operating voltages as agreed upon by the transformer subcommittee as a reference for standardized transformer design. However, there may be installations where it is thought that the lightning condition may be less or more severe than average and in consequence the next lower or next higher insulation levels may be obtained by specifying the proper test gap. The 60 cycle test will be changed according to established rules.

The strength of transformers built before impulse tests were standardized is generally lower than that of present day designs. The manufacturer can usually make a reasonably good estimate what the impulse strength was when new. The estimated strength will generally be stated in terms of the test gap which might have been used, but voltage values also may be given. The transformer may have lower strength than would be given on modern designs and this must be considered in a protection problem.

Types of Overvoltages

The problem of transformer protection may be considered on the basis of 3 types of lightning overvoltages: first, traveling waves; second, direct hits closely adjacent to the station; and third, direct strokes at the station. Traveling waves impose a relatively slow rate of voltage increase and the currents through a protective device are limited by the surge impedance of the line. Direct strokes closely adjacent to the station will impose a varying rate of voltage increase and the tail of the wave may or may not be of appreciable duration, depending upon the ground resistance, distance from the substation and the energy in the stroke. Direct strokes at the station may impose extremely rapid rates of voltage rise and in the more severe cases flashover or failure may occur on the front of the wave, especially in those installations in the lower voltage range. In considering the protection problem of transformer installations, the 2 limiting types of overvoltages, traveling waves, and direct strokes at the station, will be discussed. The intermediate case of direct strokes close to the station will dictate protective equipment in either one of the above classifications depending on local conditions, type of substation to be protected, and characteristics of the protective device. During the past 10 years, very considerable improvement has been made in the protective characteristics of lightning arresters, and in the knowledge of lightning strokes, which facts should be considered in any modernization program or new installation.

There are several combinations of equipment that can be used for protection against traveling waves.

The great majority of installations use lightning arresters; a small percentage use rod gaps either alone or in combination with arresters.

Protection Against Traveling Waves

Plain rod gaps will limit, by flashover, the magnitude of voltage applied to the station equipment. They may be considered as giving the minimum of protection, giving a degree of protection for traveling waves, and actually very little or no protection at all for steep front waves unless the gap is set low. For instance, unless the setting of the gap is considerably lower than that used in the impulse test on the transformers, the margin of safety provided by the gap will be less when the time to flashover is short or it may entirely disappear. This is because the volt-time characteristic of the rod gap shows a greater increase in flashover voltage when the time to break down is short than does transformer insulation. If the setting of the gap is reduced sufficiently to attempt to provide a margin of safety at the shorter times, the gap would flash over unnecessarily on the slower and longer waves. In addition, the gap on this setting may flash over on switching surges causing outages and the consequent interruption of service.

The ideal protective device should have ability to discharge any surge and limit the voltage to a level that would provide a reasonable margin of protection to the transformer insulation. In the case of traveling waves, where the current is limited by the surge impedance of the line, the current to be handled by the protective device is small compared to that which can appear in a direct stroke. Lightning arresters available have no difficulty in meeting these requirements provided a reasonable installation layout is provided. Modern lightning arresters are not affected by the polarity of the impulse or the shape of the wave, and are uninfluenced by weather conditions. Transformer insulation is also unaffected by these factors, which means that margins between arrester characteristics at a given current and transformer insulation will be maintained. Lightning arresters can be used as a basis of determining the proper level for other apparatus, assuming of course that the arresters are properly applied. They should be connected directly and located as closely as possible to the apparatus to be protected.

Since the protective level of the arrester depends upon the rating of the arrester used, it is always of importance to keep overpotentials at system frequency to as low a level as economically possible. Thus, a grounded neutral system may permit the use of an arrester of lower rating than can be used on an ungrounded system. These factors should all be given careful consideration, as they affect not only the cost of the arrester but may affect the cost of more expensive apparatus.

Protection Against Direct Strokes

The extent to which protection against direct strokes should be provided will usually be dictated by economic considerations. It may be decided to: (1) attempt to co-ordinate the transformer insulation so that it will withstand direct strokes; (2) use a lightning arrester which can give protection on the steep fronts of the direct strokes, the limits of the protection depending upon the magnitude of the current in the surge and the voltage class of the insulation; or (3) eliminate as far as practicable the possibility of apparatus being exposed to direct strokes.

The first method may be accomplished to a limited extent either by the use of transformers having a higher impulse strength than normal, by the use of a rod gap with reduced setting, or by a combination of both. The limitations in the protection afforded by the use of a rod gap are the same as discussed in the previous section.

Because of limitations in the protection afforded by ground wires on low voltage systems, as will be discussed later, and for economic reasons, the second method, the use of lightning arresters alone, is all that can be considered for less important and low voltage substation equipment. This is particularly true in the case of distribution transformers. This practice is not as bad as it would at first appear, as there is and should be maintained, in general, proportionately more insulation in the low voltage transformers compared to arrester rating. This allows the arrester to handle higher surge currents and still provide protection to the transformer insulation.

The third alternative, that of eliminating the exposure of apparatus to direct strokes, appears to be the best method of protecting equipment. There are a number of schemes which give different degrees of protection that are essentially the same as for traveling waves supplemented by ground wire protection. The scheme frequently used for high voltage systems comprises ground wires over the station and extending out on the line with a lightning arrester in the substation.

The method, using lightning arresters and ground wires, presents as high a grade of protection as can be suggested for substations. The ground wires extending for 2,500 feet or more should be closely associated with the station grounds and will protect for direct strokes up to their protection level. If a flashover occurs from the ground wire to a conductor, the surge will be discharged from the ground wire to ground and through the arrester to ground in parallel, thus reducing the duty on the lightning arrester.

The protection provided by ground wires has limitations dependent on the design. Where ground wires are installed, the footing impedances should be as low as possible and the clearances and spacings of the ground wires should be such that they will always take the stroke and provide an adequate shield to the phase conductors and busses.

For economic reasons, ground wire protection naturally cannot be considered on the small low voltage substations and on distribution transformers which are spotted very frequently on a distribution system. It is important in this case as well as in all cases to keep the protective device directly connected and located as closely as possible to the apparatus to be protected. The use of schemes interconnecting the primary distribution lightning arrester ground, tank and transformer secondary

neutral eliminates the effect of distance and ground resistance in the arrester performance. Similarly, better protection to power transformers is assured when the lightning arrester is connected directly and located close to the transformer.

Modernization of Relay Systems

Relay systems used for the protection of power transmission networks are now available which are greatly superior to those in use some 5 years ago. The principal change has been the development of the high speed relay, the operating time of which may be as low as one cycle or less on a 60 cycle system. Modernization of existing relay systems frequently may be accomplished by the addition of the new relays to the present relay scheme, thereby avoiding the cost of an entirely new relay system. High speed relays, especially when used with high speed circuit breakers, result in reduction of damage at stations and on lines, and give improved system stability and operation; reduction of outages on equipment of industrial customers has been an important advantage. This paper on modernization of relay systems is presented under the sponsorship of the relay subcommittee of the A.I.E.E. committee on protective devices.

By
C. A. MULLER
Membership Application Pending

H. E. TURNER
ASSOCIATE A.I.E.E.

Both of the American Gas & Elec. Company, New York, N. Y.

WITH the period beginning about 1930, when engineering attention began to be turned from the problems of constructing additions to physical property to the problems of more economical and efficient operation of existing properties, the general subject of rational modernization of many elements of such systems began to receive a great deal of attention.

Perhaps no phase of the subject was entitled to, or received more attention, than that of system relay protection schemes which form the nervous system of the large integrated transmission networks with their generating stations, which have in the last few years made interconnected utility system operation the complex technique that it is today.

The present paper reviews briefly the status of the relay art at the beginning of that period and describes the developments which made possible the modernization programs later carried out by some of the large groups of companies throughout the country. The advantages of the newer schemes of relay protection are described and operating experiences of one large system before and after its modernization program was carried out, are given.

Status at the Beginning of 1930

At the beginning of the period referred to, transmission system relaying schemes in use employed singly or in various combinations, the following:

1. Time delay induction overcurrent protection.
2. Time delay induction overcurrent protection in combination with directional power relays.
3. Directional ground current protection.
4. Balanced schemes: (*a*) current balance; and (*b*) duo-directional power balance.
5. Differential schemes for generators and transformers, and to some extent for busses, using current operated relays.
6. Time delay distance (impedance and reactance) relays.

The usual practice for stub transmission lines and for lines radiating from generating stations, was to install only time delay overcurrent protection employing induction overcurrent relays. On transmission system loops, the usual practice at substations was to install time delay power directional protection employing power directional relays in combination with time delay induction overcurrent relays. On some systems, in addition to the foregoing, ground current directional relays were used for ground faults. Double circuit lines radiating from generating stations were usually protected for fast clearing of single line faults by current balance relays in addition to time delay overcurrent protection on each line, for single line operation, and for simultaneous trouble occurring on both lines. Double circuit lines at substations were usually protected for fast clearing of line faults by duo-directional power balance relays in combination with fast set time delay overcurrent relays in addition to the usual time delay power directional protection on each line, for single line operation and for simultaneous trouble occurring on both lines. The use of differential schemes was confined mostly to the protection of generators and large transformer banks and the relays most commonly used were instantaneous overcurrent for generator protection and time delay overcurrent for transformer bank protection, although

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to some extent percentage unbalance current differential relays were beginning to be put to use for both generator and transformer protection. On some transmission system networks time delay impedance and reactance relays were being used, but to a rather limited extent.

At about the same time, another phase of relay protection which was beginning to be given serious consideration was the protection of industrial customers' installations. With the operation of large interconnected systems rapidly becoming the general rule throughout the country, system disturbances were beginning, with the rather long relaying times which had to be contended with, to give serious trouble because of the effect of voltage dips which were transmitted over rather wide areas. One of the first serious troubles which this caused, in addition to those problems connected with interconnected system operation itself, was interruption to service of industrial customers whose equipment was not provided with the proper relay protection. The standard forms of protection for industrial control equipment up to that time had been the following:

1. Time delay overcurrent protection, usually employing dash-pot overload relays.
2. Instantaneous undervoltage devices.

The principle cause of trouble encountered was due to the use of instantaneous undervoltage protection, which functioned on voltage dips of comparatively short duration to disconnect the customer's equipment from the transmission lines.

The Need for Improvement

The growth of transmission and generating systems, and the extent to which such systems were being interconnected, referred to above, naturally brought about a great many new operating problems. One of these problems was that of stability in operating heavily loaded tie lines. When faults occurred on such lines, the long relay times for clearing them, in many cases, resulted in sections of the system pulling apart as a result of the disturbance. With increased system capacities and the consequent large amounts of current fed into transmission system faults, and with the rather long relaying times, physical damage upon the occurrence of such faults was becoming more and more serious. Oil circuit breakers which had previously had adequate ratings were being subjected to duties which they were not capable of performing, and breaker failures became more prevalent. Actual burning of conductors was getting to be a very serious problem. The transmission of voltage surges over a whole system upon the occurrence of trouble on one portion of it was beginning to cause more serious trouble, particularly with respect to industrial customers. The thing urgently needed and offering the most toward solution for many of the operating problems of interconnected systems, was means for faster clearing of faults on the system which could only be obtained by increasing the speed of both relaying schemes and circuit breakers.

This need for speed is well recognized today, and particularly on systems involving extensive interconnections and with heavy concentrations of power. High speed is obviously a relative term. Not so long ago, and well within the memory of many engineers practicing today, system disturbances were cleared by hand after hanging on for periods running into minutes. About 10 years ago it was considered good relaying practice to be able to clear a fault in a maximum relay time of 2 seconds. By about 1930, these times had been cut in almost every case to less than 1.5 seconds and the average over-all time for clearing a fault varied from about 45 to 75 cycles. Today, the term "high speed relaying" is considered

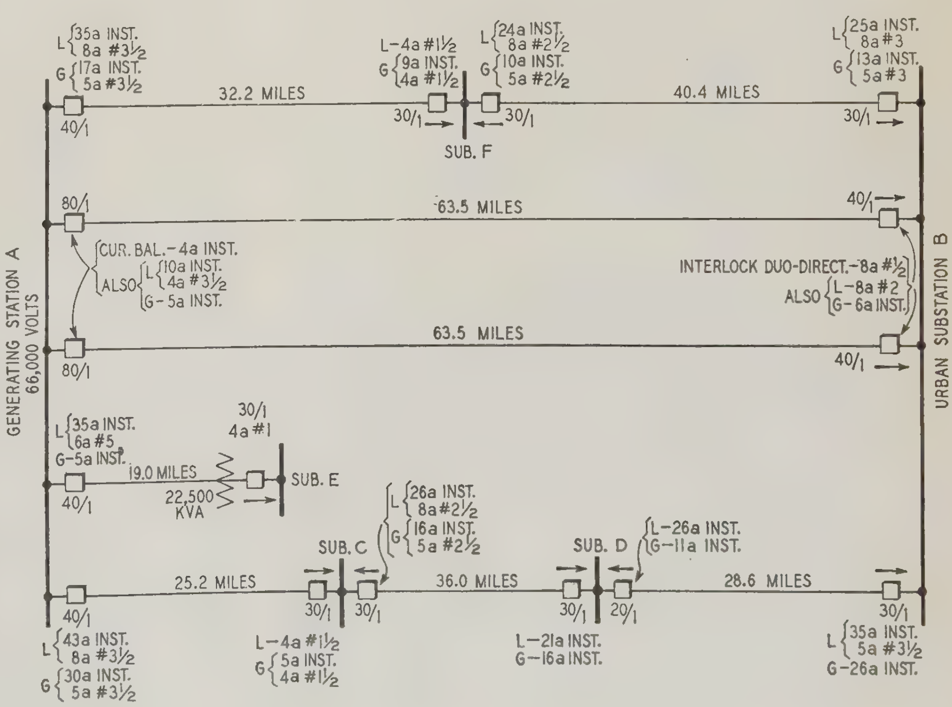

Fig. 1. Instantaneous relaying of a typical transmission network

LEGEND

L indicates phase relay settings
G indicates ground relay settings
(*20aINST*, for example, indicates instantaneous current relay settings of 20 amperes and instantaneous time)
(*8a#2*, for example, indicates time delay induction overcurrent relay settings of 8 amperes and number 2 time)

→ indicates reverse power phase and ground relays, settings of which are shown. (Where no arrow is indicated alongside of a circuit breaker the accompanying *L* and *G* settings are for relays giving nondirectional overcurrent protection)

40/1, for example, indicates ratio of current transformer

to apply to time intervals of the order of from 4 cycles maximum to a minimum of a fraction of a cycle from the time of the occurrence of the fault to the energizing of the trip coil. With high speed breakers that are being produced now, the over-all time that it is quite practical to obtain very seldom exceeds 12 cycles, and in many cases is less than 8 cycles.

Developments Required for Improvement

As previously indicated, high speed circuit breakers and relays obviously offered the most satisfactory means in solving interconnected system operating problems. Any program, then, of modernizing existing relay systems to obtain faster clearing of faults, will be effected by introducing faster relay functioning in the existing schemes. This may be accomplished either by superimposing high speed relays on existing schemes which, as shown later, will give high speed relay protection for approximately 90 per cent of the cases of trouble that occur on transmission systems, or by the substitution for existing schemes of some form of high speed relaying which will give complete protection for any line section under any fault conditions.

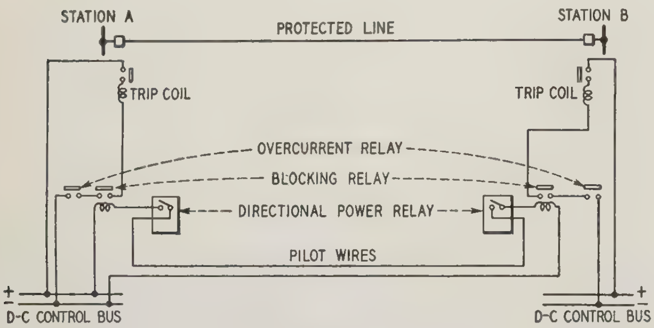

Fig. 2. Elementary diagram of metallic pilot wire relaying

Although it became apparent about 1930 that high speed operation of circuit breakers and relays would provide the answer to these problems, the necessary equipment had not yet been made generally available.

One of the first steps taken by the operators and manufacturers was an investigation of the possibilities in redesigning existing circuit breakers so that with the addition of suitable parts they could be converted for high speed operation and at the same time have higher interrupting capacities. These efforts resulted in a satisfactory high speed oil circuit breaker being made available for those operating companies desiring to rebuild and modernize their existing switching equipment.

About the time that this work on circuit breakers was begun, the development of high speed relays was started by the manufacturers, and some of the utility companies started to modify existing relay systems to give faster relay operation. Such a modification worked out and applied about 5 years ago on some of the large systems was that of using instantaneous overcurrent phase and ground relays in conjunction with the already existing induction overcurrent directional power installations to give high speed protection for the majority of transmission system faults.

New high speed relays to perform the same functions that the old relays did, but with much faster operating times, became available. Among these were the following:

1. High speed overcurrent relays.
2. High speed directional power relays.
3. High speed directional ground relays.
4. High speed current differential relays.
5. High speed distance relays.
6. High speed auxiliary relays.

At the same time that this development toward higher speed breakers and relays was being carried out, attention was turned to solving the problem of providing proper relay protection for industrial customers' equipment. The most effective means of providing such protection for these customers was changing their control circuits by using time delay undervoltage devices and providing means for unloading synchronous motors carrying heavy loads, which could not ride through disturbances even with proper undervoltage protection unless their loads were reduced. This led to the development by equipment manufacturers of suitable undervoltage protective devices with the necessary time delay features, for application to existing equipment, and to be furnished as standard with new equipment. In addition, auxiliary devices, such as, for instance, magnetic unloading valves for large synchronous motor-driven compressors, were made available, and control wiring schemes were redesigned to permit automatic resynchronizing of synchronous motors.

Application of High Speed Relays in Modernizing Relay Systems

These developments were of great interest to operating engineers because of the possibilities offered for modernizing existing schemes of relay protection. These possibilities were of 2 general kinds: first, the superimposing on existing relay installations of high speed relays to give fast protection for the greater majority of transmission system faults; and second, the working out of new schemes of relay protection which could be applied on important parts of the transmission system, such as on important tie lines, to give complete high speed protection for all types of faults.

The possibility having the most general application over the whole transmission system is the first one. This method of modernization, too, has in most cases proved to be the most economical. Possibilities of the second kind have been much more limited and usually are more expensive to apply. For this reason the applications of these schemes have been limited to particular locations where there has been some very definite justification for them.

Some of the more common high speed relay

schemes which have been installed within the past 7 year period are described in the paragraphs which follow. The majority of these applications have been made primarily to modernize existing system relaying and it is only in exceptional cases that the adoption of these newer schemes has resulted in the complete abandonment of existing relay installations.

1. Instantaneous Overcurrent Protection

Probably the most effective and certainly one of the most economical schemes employed in the general modernization of transmission system relaying to obtain high speed clearing of the great majority of all kinds of transmission system faults has been the superimposing of instantaneous overcurrent relays on existing relay systems. This scheme employs 3 instantaneous overcurrent relays per circuit, 2 of which are connected as phase relays and the third as a ground relay. The instantaneous phase and ground relays work in conjunction with the directional power and induction time-delay overcurrent relays already installed. They are set to pick up at values of phase and ground currents which are slightly greater than the maximum current that would flow from the bus to the line on a through fault, for any line section. With these relays so set, instantaneous relay action (one cycle) is obtained in all cases for faults covering up to approximately 90 per cent of the line section. In addition, in many cases, after the breaker at one end of the line section opens the relay settings on the breaker at the other end, with the increased current flow through that breaker, will cover the entire line section causing the latter breaker to trip immediately after the first one.

A very decided advantage which the installation of instantaneous overcurrent relays gives is that the time delay induction overcurrent relays can have their settings materially decreased since these need only cascade with each other for a fault at the end, instead of at the beginning, of a line section. In the case of a typical loop circuit, say one containing 5 sectionalizing stations, and extending out from one generating source, the reduction in relay settings of the time delay induction overcurrent relays on the breakers at the generating station may be as much as from 60 to 90 cycles, for a fault at the end of the line section, if instantaneous overcurrent relays are installed at each of the stations in the loop.

Figure 1 shows an application of instantaneous overcurrent relays to a typical transmission network on one large system. This network is a 66,000 volt transmission system serving one large city and dozens of smaller communities in an area supplied from one large generating plant. The relay settings shown for both the line and ground instantaneous and time delay induction overcurrent relays indicate how it has been possible to lower the time settings on the time delay induction overcurrent relays. The settings of the instantaneous phase relays on this system are such that with a phase-to-phase fault of 100,000 kva flowing through a breaker, it will trip instantaneously.

This particular method of obtaining high speed operation has much to recommend it, providing as it does a very effective way to modernize many kinds of existing relay systems economically. It has been possible to modernize existing relay systems in this way to provide complete protection for the large majority of transmission system faults at a cost less than 10 per cent of that of any other scheme of high speed relay protection which would give comparable performance.

The instantaneous relays used may either be designed to fit in the cases of the existing induction overcurrent relays or they may be separate relays. In the first instance no additional panel space is required and no changes in switchboard wiring are necessary. In the second, the additional space requirements on a panel very seldom make it necessary to provide new panels and the switchboard wiring changes are comparatively simple. Where separate relays are used, it has even been found possible in some cases to recondition, at very small cost, and reuse obsolete relays which had been retired.

Where instantaneous overcurrent relays are used with existing schemes employing reverse power relays, it is possible to obtain a still further increase in speed by replacing the existing power directional relays with the new high speed types. With the instantaneous overcurrent relays used for phase protection the 3 phase high speed directional relay is provided with voltage restraint which normally holds its tripping contacts open. When a fault current operates the instantaneous overcurrent phase relays their circuit opening contacts will remove the voltage restraint from the directional relays, allowing them to operate as sensitive power directional relays. The circuit closing contacts of the instantaneous phase relays which are connected in series with the power directional relay contacts complete the tripping circuit. In general, the 3 phase power directional relay may be used with the instantaneous ground relays for ground protection but in special cases it may be desirable to employ a high speed ground directional relay with the instantaneous ground relays.

The total relay operating time using instantaneous overcurrent relays in conjunction with the older power directional relays is approximately 8 cycles, but when the high speed power directional relays are employed the over-all relay time may be reduced to approximately 1 cycle.

2. High Speed Balance Schemes for Parallel Lines

In modernizing existing relay systems it may at times be desirable to apply high speed balance protection on parallel lines without altering the normal protection for single line operation.

Usually at the supply end of such lines the existing current balance relays will be replaced with high speed current balance relays. Such an installation makes it possible to clear a fault on a single line with a relay time of approximately 0.25 cycle, whereas using the older induction current balance relays a relay time in the order of 7 to 8 cycles is required. For example, it may prove to be particularly desir-

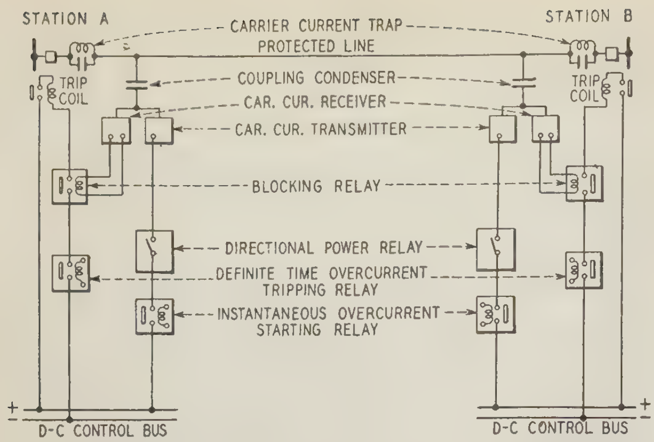

Fig. 3. Elementary diagram of carrier current relaying

able to make such changes in balance protection when circuit breakers are being rebuilt for high speed operation. Unless advantage is taken of the possibility of cutting the relay time the increase in speed of operation offered by simply rebuilding the breakers may not be warranted.

At the load ends of such parallel circuits increases in speed of relay operation of the same order may be obtained by replacing existing directional balance relays with high speed directional relays. In employing high speed power directional relays for such duo-directional balance protection 2 schemes may be used. In the first, 2 3-phase high-speed relays with voltage restraint are used in conjunction with 3 instantaneous overcurrent relays, and, in the second, single phase high speed directional relays without voltage restraint and instantaneous overcurrent relays are employed. Both schemes operate with an over-all relay time of about one cycle. Voltage restraint is employed on the 3 phase power directional relays to hold their tripping contacts normally open. In case of an unbalance current sufficent to operate the instantaneous overcurrent relays the restraint is removed from the power directional relays by the circuit opening contacts of the instantaneous relays allowing them to operate as sensitive power balance relays; the circuit closing contacts of the overcurrent relays connected in series with the balance directional relay contacts then complete the trip circuit.

Balance protection of the kind just described is limited to protecting for single line faults on 2 or more parallel lines and will not provide complete protection for simultaneous faults occurring on 2 or more parallel lines, nor for faults on single line circuits. To obtain high speed relaying under these conditions it is necessary to resort to some other scheme. One scheme of this kind is that already described, i. e., the superposition of instantaneous overcurrent relays on existing protective systems.

3. High Speed Distance Relays

Another method employed on many systems to furnish high speed protection is the use of high speed distance relays. Relays of the so-called distance type have been employed for many years. These relays have been of 2 general types—the impedance relay and the reactance relay. On some complicated transmission networks involving a large number of sectionalizing stations connected in series, and also wide variations in generating conditions, the application of distance relays has been warranted both because relay times could be kept from becoming too long and because the time required to clear a fault could be made independent of the variable generating conditions.

The older types of distance relay schemes had the same disadvantage as the power directional-time delay induction overcurrent relay combination. With both of these relaying schemes no fault on any part of the line section was cleared instantaneously. The development of the high speed distance relay has made it possible to obtain instantaneous relay operation for approximately 90 per cent of any line section. The high speed distance relay includes up to 3 component parts: an instantaneous element; a time delay element; and, when used, a second time delay element, generally set for a time longer than the first time delay element. It is interesting to note, in comparing high speed distance relay schemes with schemes involving instantaneous overcurrent relays superimposed on power directional-time delay induction overcurrent relays, that the performance of the 2 relay schemes is very similar, that is, the instantaneous relays perform the same functions as the instantaneous elements in the distance relay and the time delay induction overcurrent relay performs the same function as the time delay elements in the distance relays. In general, however, up to the present time, distance relays have been designed for phase-to-phase protection only and in only special cases for ground protection. This is a restriction to which the superposition scheme has not been limited. The high speed distance relay is not as applicable to superposition schemes as the other relays discussed, since usually it is difficult, and sometimes it is impossible, to co-ordinate them with existing relay schemes. Usually such a system of relays will be either installed initially or will replace existing schemes.

On many complicated transmission networks of the kind previously referred to, it has been found economically justifiable to install distance relays because such installations offered some advantages over the superimposed instantaneous overcurrent relay scheme.

4. Universal High Speed Relaying Schemes

Although the various relay schemes just described do give high speed relaying for the great majority of transmission system faults, they do not give complete and rapid protection to any line section over its entire distance, regardless of the type of fault. On important line sections such as short parallel lines radiating out from generating stations and on single and double circuit tie lines connecting 2 generating sources, with a series of sectionalizing stations in between, it is necessary that all types of faults, including ground, phase-to-phase, and si-

multaneous faults on 2 circuits, be cleared as quickly as possible to maintain the stability of the system.

The only relaying scheme which will provide complete protection of this kind is some form of differential protection for the protected section, similar, for instance, to differential protection provided for a generator, transformer, or bus. The 2 most successful and practical forms of this kind of protection are afforded by (*a*) metallic pilot wire schemes; and (*b*) carrier current pilot relaying.

High Speed Metallic Pilot Wire Schemes. Until recently, pilot wire protection was the only relay scheme proposed which would give complete and fast protection to any line section over its entire distance, regardless of the type of fault and the number of line sections between any 2 sources of supply. While this scheme has been used in this country for a number of years, it has been applied to a somewhat limited extent only, and then principally for short lines. The high cost of pilot wire circuits, particularly for long lines, and the operating difficulties with such circuits, have in the past hindered the progress of metallic pilot wire schemes. Within the past few years, however, such schemes have been simplified and made very reliable by the use of high speed directional power relays in conjunction with leased telephone circuits serving as the pilot wires.

With such schemes the directional relays are used to determine by directional comparison whether a fault is internal or external to the protected line section. Usually the power directional relay is so connected that for power flow from the bus into the line it closes its contacts. When a fault occurs in the protected line section power will flow from the bus into the line, at both ends, and the contacts of the power directional relays at both ends will close. These contacts are connected in series with the pilot wires to energize circuit-closing blocking relays at each end of the line, which action completes the trip circuits and causes simultaneous tripping of both breakers. For a fault external to the protected section, the contacts will close on only one of the power directional relays and neither of the blocking relays will be energized, which will block the trip circuits of the breakers at both ends of the line. The principle of operation of such metallic high speed pilot wire schemes is shown in figure 2. There are, of course, many variations in pilot wire schemes but most of the modern ones depend upon the principle of using power directional relays to indicate by directional comparison whether the fault is internal or external to the protected line section.

Carrier Current Pilot Relaying. About 1927, in the search for a high speed universal relay scheme, development work was started on an application of differential relaying employing carrier current over transmission lines to perform the functions of pilot wires. This work was continued and has culminated in the development of thoroughly practical, simple, and inexpensive carrier current relay protective schemes. Most of these schemes have been described in the technical press, and relay engineers are well acquainted with their details.

This form of protection is well suited in any program of modernization for use at many points on a transmission system, since it can be used either superimposed on existing relay schemes or to replace them. Carrier current relay protection can be applied to any line section on a transmission system without it affecting in any way the operation of any existing relay schemes on other sections of the network. In addition, on those systems where carrier current communication is installed, carrier current relaying can be applied very economically because existing coupling capacitors can be utilized for both purposes.

Like high speed metallic pilot wire protection, all of these carrier current relaying schemes depend upon the use of high speed directional power relays to determine by directional comparison whether faults are internal or external to the protected line section.

Figure 3 shows in an elementary way how such a carrier relaying scheme operates. For an external fault beyond station B the power flow at station B is from the line into the bus causing the directional and instantaneous overcurrent starting relay contacts to close, which starts the transmission of carrier current at station B. This carrier current operates the receiver sets at both ends of the line which in turn operate the blocking relays at both stations and prevent tripping of the circuit breakers. For an internal fault the power flow at both stations is from the bus into the line and both directional power relays open their contacts and no carrier current is transmitted from either station. After the contacts of the tripping relays close, both circuit breakers will then trip.

Many of these carrier current systems operate with an over-all relay time of from 2 to 5 cycles. Some of the most recently installed systems will operate with an over-all relay time of less than one cycle. When this system is used in conjunction with 3 cycle high speed circuit breakers, the total over-all time from the occurrence of a fault to the opening of a circuit breaker is less than 4 cycles. With system disturbances cleared in such short times, almost any equipment connected to the transmission system is

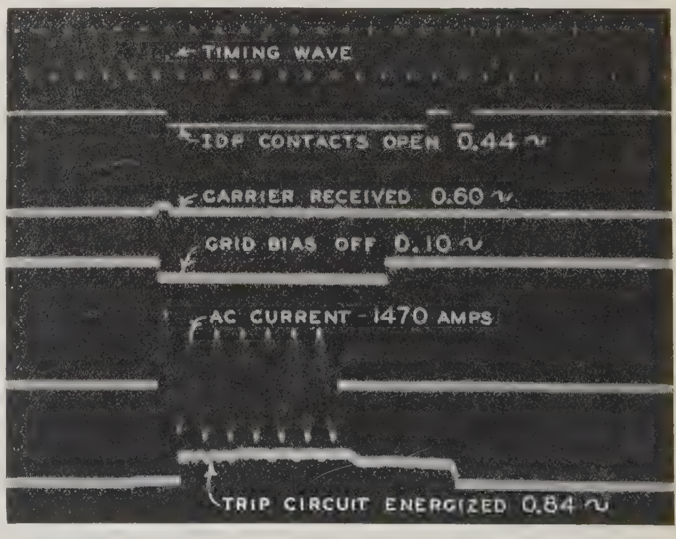

Fig. 4. Oscillogram showing speed of operation of carrier current relaying on an internal fault

IDP indicates a power directional relay

completely insensitive to the disturbance. In figure 4 oscillograms are shown which were taken on tests of one of these new carrier current relaying schemes. It will be noted that the trip circuit was energized in 0.84 cycle after the inception of the fault.

5. High Speed Bus Differential Protection

One outstanding step in relay modernization which has been made particularly within the past 5 years has been the installation of high speed differential protection on important busses. This form of relay protection pays large dividends in reducing the severity of transmission system disturbances and in lessening equipment damage upon the occurrence of a bus fault. Moreover, bus differential relaying schemes are simple, reliable, and usually economical to install. In its simplest form this protection employs instantaneous overcurrent relays connected in a differential circuit using the bushing current transformers installed in the oil circuit breaker bushings.

Differential protection of generators and transformers has been quite generally employed for a number of years. However, when any modernization program is contemplated, serious consideration should be given to extending transformer differential protection even to many transformer banks of moderate capacity which have perhaps not been provided with such protection. Existing transformer differential and generator differential schemes can, in some instances, be made faster and more sensitive by the employment of the newer high speed current differential relays.

6. Protection of Industrial Equipment

During the past 5 years, much development work has been carried out on protection of industrial equipment to prevent unnecessary interruptions in service for trouble occurring on transmission systems. The chief trouble with previous schemes of protection on industrial control equipment was caused by the use of instantaneous undervoltage protection which made motors drop off the line in câse of a voltage surge, even though the duration of the surge was very short. Undervoltage devices have been developed which can be used to replace instantaneous undervoltage devices and give time delay undervoltage protection. On some of the older control schemes where a-c contactors energized from the transmission system, were employed on motors, the control circuits have been energized from a d-c source or latched-in contactors have been used. On large synchronous compressor motors which were very sensitive to dropping out of step on voltage surges, automatic magnetic unloaders have been applied which unload the motors on the occurrence of a voltage surge and allow them to run as induction motors. After the system voltage has returned to normal, the synchronous motors resynchronize and automatically take up the load again. All of these schemes for protection of industrial apparatus have proved to be very effective and they are economical and easy to install. These very necessary changes to industrial control equipment have, by themselves, been of great benefit and with the increased speed of system relaying which has come about, service complaints from industrial customers have been practically eliminated.

Results Obtained

The value of these relay developments and applications of relay systems just described must, of course, be judged by the results which it has been possible to obtain with their use. On those transmission systems where modernization of the kind just described has been carried out, the following very definite advantages have been realized:

1. *Reduction of Damage at Stations.* Where high speed relaying has been used, damage to equipment and to structures has been negligible. This is true even with heavy concentration of power at the point of fault. Usually the trouble results in nothing more than switch openings.

2. *Reduction of Damage on Lines.* Burning of high voltage transmission line conductors of the larger sizes is reduced to slight pitting. Insulator damage is reduced to slight markings on the surface of the units or only a discoloration of the glaze. The burning apart of transmission line conductors has been almost eliminated, with consequent reduction in maintenance costs.

3. *Improved System Stability.* The operation of interconnected transmission system networks has been very greatly improved where faults are cleared rapidly. With the decrease in relay operating times, the amount of power that can be transmitted over tie lines before instability occurs has been very appreciably increased.

4. *Improved Interconnected System Operation.* The complicated problems of proper frequency and load control are materially simplified by high speed relaying through the elimination of system disturbances of long duration and the splitting apart of sections of the system.

5. *Reduction of Service Outages.* Long interruptions are very seldom experienced where high speed relaying is employed. When a fault does occur, the chance of the oil circuit breaker staying closed upon reclosure is very much better because of the limited damage with high speed relaying.

6. *Improved Service to Industrial Customers.* High speed relaying in conjunction with improvements made in industrial customers' control equipment has almost eliminated interruptions to service to such customers and the consequent costly delays in production schedules.

From the above results it is obvious that the use of high speed relaying schemes and high speed circuit breakers has done a great deal to improve the operation of interconnected systems. The application of the developments which have been described has made possible the solution of a number of difficult operating problems, and the further extension of new developments of this kind will no doubt aid in solving some of the remaining problems.

Operating experience indicates clearly that these relaying schemes and the devices used with them are extremely reliable, and that very little concern need be entertained about how such systems will operate when called upon. These various high speed relaying schemes, in addition to being practical and reliable, are also usually justifiable economically.

A great deal of credit is due to the engineers responsible for the various developments in the protection art which have been described, and these men have a right to take pride in their contributions to the advancement which these developments have brought about.

Lightning Investigations on a Distribution System

Analyses of field measurements of lightning disturbances and of operating experience on a metropolitan electric power distribution system have yielded valuable information on protective methods. Performance records of transformers, fuses, lightning arresters, meters, and customers' equipment with the interconnection method of protection (arrester ground and secondary neutral interconnected) are analyzed. Experience with protective methods for underground cables and for stud type of distribution transformers is cited, and an a-c method of testing arresters is described.

By
HERMAN HALPERIN
MEMBER, A.I.E.E.

E. H. GROSSER
NONMEMBER

Both of Commonwealth Edison Company, Chicago, Ill.

INVESTIGATIONS of operating experiences and special laboratory and field tests in connection with lightning disturbances on the 4,000-volt 3-phase distribution system in Chicago, Ill., have been extended from the work covered in previous papers,[1,2] and new lines of study have been undertaken. From the results of these researches the following conclusions have been derived. Although strictly applicable only to conditions in Chicago, many of these conclusions may prove to be of value for other systems:

1. In comparison with normal arrester protection, interconnection of the lighting arrester ground lead with the lighting secondary neutral mains on the overhead distribution transformers (hereafter called simply "interconnection") has had the following effects on rates of lightning troubles: transformer burnouts, 49 per cent decrease; fuse blowings, 67 per cent decrease; arrester failures, 47 per cent increase; meter failures, small increase; troubles on customers' equipment, no increase.

2. At transformer locations with interconnection, from 200 to 300 surges of 5 kv or more occur to one case of trouble. Less than 15 per cent of surges exceeding 100 kv appear to result in transformer damage.

3. Measurements of lightning surges indicate that for most surges the potential of the ungrounded transformer tank remains near ground potential. This permits high surge voltages to appear across the transformer bushings in spite of the protection afforded by the arrester, accounting for many of the lightning troubles that still occur with interconnections.

4. A surge voltage drop along the ground connection between arrester and secondary neutral of one kv per foot is not unusual, and higher values may occur. This points to the advisability of installing the arrester on the transformer pole where economically feasible, and of using short ground connections for interconnections.

5. Other causes of transformer failures and fuse blowings attributable to lightning which still occur with interconnection are (*a*) old or defective transformer coil or lead insulation, or both, and (*b*) high arrester breakdown voltages resulting from steep surges.

6. Interconnection between arrester ground lead, extended secondary neutral wire, and cable sheaths should greatly reduce the possibility of lightning damage at such locations.

7. Voltages covering $^2/_3$ of a mile of semirural line, with maximum values of 500 kv, have been measured.

8. Distribution transformers of the type used in Chicago having replaceable exposed stud type of bushings appear less likely to fail but more susceptible to bushing flashovers causing fuse blowings than lead type transformers during early service.

9. Where the transformer tank is not grounded, fewer lightning troubles may be expected if the surge flashover voltage of the secondary neutral bushing is reduced to 10 or 15 kv.

10. Where direct grounding of the transformer tank is employed, the tank should be grounded preferably to the secondary neutral main at or near the transformer in order to reduce lightning troubles.

11. Investigation of lightning damage to meters indicates the primary cause to be insufficient clearances between leads or terminals and case, and also, for the motors of demand registers, the low surge current capacity of the fine wire.

12. Satisfactory lightning protection for underground distribution cables more than 2,000 feet in length probably can be obtained by arresters installed on the overhead portion within 500 feet of the cable poles.

13. A method of testing used lightning arresters by measuring the a-c leakage current at normal operating voltage and the a-c breakdown voltage has proved satisfactory.

Distribution System

Descriptions of the distribution system in Chicago have been published previously.[1,2] The primary neutrals are grounded at the substations only. Underground cable extends from substations to cable

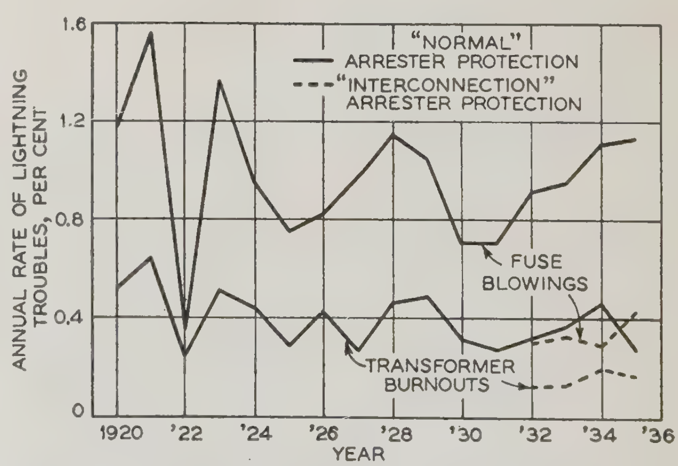

Fig. 1. Reduction effected by interconnection in transformer troubles caused by lightning

Percentages for 1935 are estimated from data as of October 1, 1935

A paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 28–31, 1936. Manuscript submitted Oct. 21, 1935; released for publication Nov. 20, 1935.

1. For all numbered references see list at end of article.

poles and connects to 4-wire 3-phase overhead circuits which comprise the major portion of the system. Arresters are installed on primary wires at all cable poles, except for experimental removals, and at 70 per cent of the transformer poles, other transformers being one to a few spans from an arrester. The arrester grounds and the secondary grounds for transformers average about 15 ohms. Also, about 92 per cent of the secondary neutrals are grounded to water pipes in customers' premises, resulting in a combined ground resistance of less than one ohm. As a safety measure, transformer cases are not grounded.

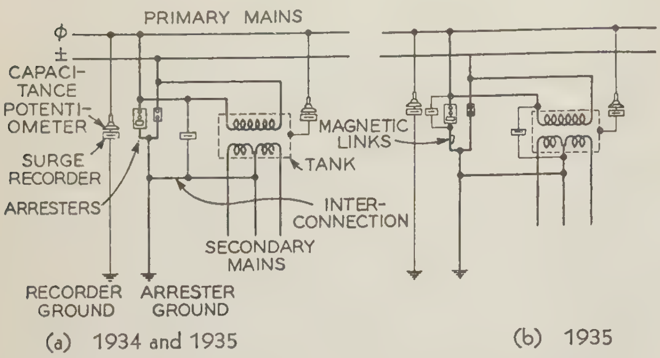

Fig. 2. Special installations of surge recording devices at locations of interconnections

Interconnection

Beginning in 1932, the lightning protection scheme has been changing gradually to one comprising interconnection of the arrester ground lead and lighting secondary neutral main. By October 1, 1935, some 25,000 overhead transformers, or 76 per cent of the total on the system, had this method of protection; for 30 per cent of these transformers the arrester protection is one or a few spans away, since it has not seemed essential to employ more than one arrester for 2 or more transformers on the same phase in a block. In making interconnections, the conservative requirement of grounding the secondary neutral to 2 water pipe grounds in customers' premises has been followed.

During this 4-year period, interconnection has effected the following results in comparison with equipment having the older method of "normal" arrester protection, in which the phase and neutral arresters are connected only to a driven pipe ground:

Table I—Surge Voltages Recorded on the 4,000 Volt Overhead Distribution System in Chicago

Surge Recorder Installations: Type of Location	Number	Average Number of Times Surges Were Recorded per Year*: Total	Per Installation
Transformer	26	40.5	1.56
Cable pole	4	4	1.00
Long circuit	2	5.5	2.75
Total	32	50	1.56

* Average for 1934 and 1935 records. Data for 1935 include records to October 1.

Beneficial Results

1. A 49 per cent decrease in the rate of transformer failures (figure 1).
2. A 67 per cent decrease in the rate of fuse blowings (figure 1).
3. No increase in the previous low rate of troubles to customers' equipment.

Undesirable Results

1. A 47 per cent increase in the rate of arrester failures, apparently caused by higher duty on arresters in transmitting high surge currents to relatively low resistance grounds. This increase is of little importance economically as it causes only 15 or 20 more arrester failures per year than occurred with normal arrester protection. Furthermore, little, if any, increase has been found for the rate of failure of modern valve-type arresters.
2. An increase, based upon one year's records, of about 25 per cent in the rate of meter burnouts, involving chiefly the motors of demand meters. The rate of meter failures caused by lightning is relatively low.

Laboratory tests[3] conducted prior to 1932 and subsequent measurements[2] of lightning voltages on the overhead system by means of surge voltage recorders had indicated that, with interconnection, the surge voltages to which distribution transformers would be subjected in service would be limited to approximately the arrester breakdown voltage or about 20 kv. Yet, in spite of the interconnection, transformer fuse blowings resulting from flashover around bushings, and failures of windings still occurred at a reduced rate, although the impulse strengths of the winding and bushing or lead insulations were apparently several times the arrester breakdown voltage. Therefore, further investigations, as later described, were undertaken.

Surge Recorder Investigation

Installations. Surge voltage recorder installations in 1934 and 1935 included 8 transformers and 2 cable poles with normal arrester protection, 18 transformers and 2 cable poles with interconnections, and 2 long circuits. Figure 2 shows surge recorder connections at locations of transformers with interconnections; connections were made as in (*a*) to measure the potentials of the primary phase and secondary neutral wires and of the ungrounded transformer tank. In 1935, to investigate the voltage drop in the ground connections between arrester and secondary neutral, 4 surge recorders were connected at 8 locations as in (*b*) for the purpose of comparing the voltage across the arrester with that between the transformer terminals.

In order to measure the surge currents discharged through the phase lightning arresters, surge crest ammeters of the magnetic link type[4] were installed late in 1934 at all surge voltage recorder installations, as indicated in figure 2(*b*), with the co-operation of the General Electric Company; in addition, about 300 of these devices were installed elsewhere in the city.

Surge Voltages Recorded. The surge recorder films were replaced 3 times in 1934 and 4 times in 1935. A summary of the surges recorded is given in table I. As compared with 1.56 and 1.0 surges

Table II—Correlation of Surge Recorder and Lightning Trouble Data at Locations of Interconnections

Year	No. of Thunder-storms		Transformer Troubles Caused by Lightning: Burnouts	Fuse Blowings	Total (A)	Surges Recorded From Primary Phase to Separate Ground at 18 Locations (B), Greater Than—Kv: 100	75	50	25	10	Total	Radio of Surges to Troubles per Installation (B/A): Greater Than 100 Kv	Total
1934	41	Number	39	59	98	1	2	4	7	18	27	...	...
		No. per installation	0.0027	0.0041	0.0068	0.056	0.11	0.22	0.39	1.00	1.50	8.2	220
1935*	47	Number	39	96	135	1	2	3	8	17	46	...	...
		No. per installation	0.0023	0.0056	0.0079	0.056	0.11	0.17	0.44	0.94	2.55	7.0	320

Note: The number of transformer installations having interconnections was, in the middle of the lightning season, about 14,500 in 1934 and 17,000 in 1935.
* To October 1.

per installation per year for transformers and cable poles in the metropolitan area, the average of 2.75 surges per installation per year for long circuits indicates the disparity to be expected between lightning conditions in urban and in semirural territory. The majority of the recorded surges were of low magnitude, only 2 surges resulting in damage to equipment on poles.

Table II correlates the recorded surges at transformer installations having the interconnection with transformer troubles caused by lightning at similar locations throughout the city. The data obtained

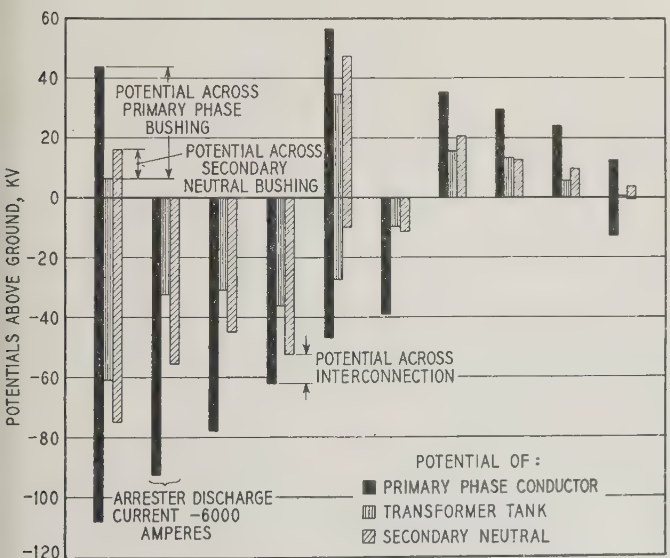

Fig. 3. Highest surge recorder records obtained in 1934 and 1935 at locations of interconnected transformers with 3 surge recorders per location

Where positive and negative surges are shown together these were recorded on the same set of films during the same period

indicate that one case of trouble occurs for every 200 to 300 surges of, say, 5 kv or more, but that for surges of more than 100 kv, one case of trouble occurs for every 7 or 8 surges.

Interconnection: The Transformer Tank. Published test results on distribution transformers[5,6] had shown that under surge conditions the transformer tank, when isolated from ground, assumes a potential somewhere between the potentials of the primary phase and secondary neutral leads, being generally nearer the latter because of the greater capacitance of the secondary winding to tank and core. Therefore it was surprising to discover, in many of the surges measured, that the floating transformer tank assumed a potential *nearer true ground* than did the primary phase and secondary neutral.

Figures 3 and 4 show graphically the 19 highest and most complete surge voltages recorded in the 2 years at interconnected transformers with surge recorders installed as in figure 2. Of the remaining measurements, the majority contained incomplete sets of records and the voltages were comparatively low. Including positive and negative surges recorded in the same period at a few locations, 17 out of 24 records indicated transformer tank potentials lower than those of the secondary neutrals by amounts ranging up to 35 kv. For the few records in figure 4 where some portions of the circuit are shown above and some below ground potential, it is believed that the potential of the primary phase wire was actually further from true ground potential than the

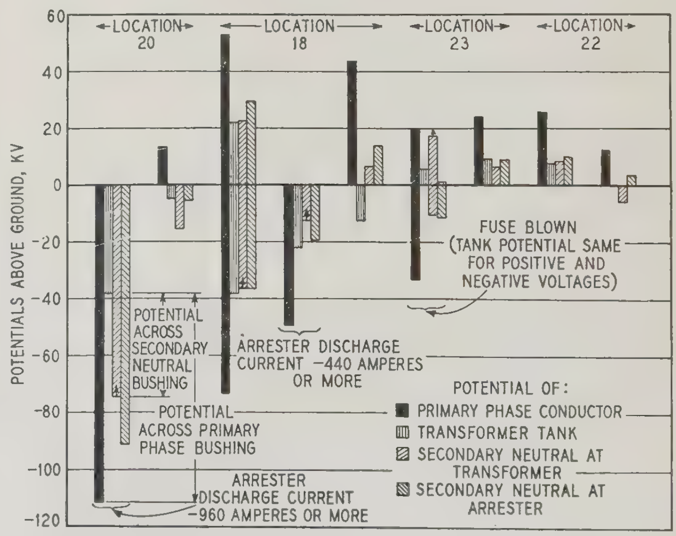

Fig. 4. Highest surge recorder records obtained at locations of interconnected transformers with 4 surge recorders per location

Arrows on voltages indicate that potentials, which exceeded the limit of the surge recorder, may have varied slightly in the direction shown

measurement to a driven ground indicated. This is of no significance, as all other potentials were measured relative to the primary phase wire. These data indicate that for average Chicago installations the transformer tank assumes roughly 50 per cent of the surge potential on the primary phase wire.

The lowering of transformer tank potential apparently can be explained by what occurs during building up of bound charges on the line wires and tank. During the relatively long period in which charges accumulate, both primary and secondary wires may be considered virtually grounded through transformer windings, and hence take up charges consistent with their positions in the cloud field. The ungrounded transformer tank, however, must assume a charge at a slower rate, because of its high resistance path to ground over either the bushings or the surface of the pole. Thus, at the end of this period, the charge on the transformer tank could be substantially lower than those on the primary or secondary wires, and its resultant potential on cloud discharge would be less. This occurrence could take place either with normal arrester protection or with the interconnection.

This finding of lowered tank potentials immediately suggested an explanation for some of the transformer troubles that occur in spite of interconnections. Where the potential of the tank remains nearer true ground potential than does that of the transformer windings, the total voltage across the primary and secondary bushings may exceed that between windings by twice the amount the transformer tank potential drops below that of secondary neutral. This would be of no significance if direct flashover or puncture occurred between primary and secondary windings, but is probably an important factor in lightning troubles with the cascading type of flashover; for example, the primary phase first flashes over to tank, placing surge potential from the primary on the tank, which then arcs to the secondary neutral. This is probably what occurred in the first case shown in figure 4 for location 23, where lowering of the transformer tank potential was apparently responsible for a blown fuse.

Interconnection: Voltage Drop in Leads. While the majority of voltages measured across the interconnection were of an order consistent with normal arrester breakdown voltages, in several cases the measured voltages were from 28 to 37 kv or more (see figure 3). These were from 13 to 22 kv more than the manufacturers' values of breakdown voltages of the particular types of arresters installed at these locations. The arresters therefore were removed from service and surge tested in the manufacturers' laboratories, with the results shown in table III. The high breakdown voltages measured in the field were not duplicated in these tests; and while some increase was found for steep-front surges, it was estimated that rates of voltage rise of from 200 to possibly 1,000 kv per microsecond would be required to obtain voltages as measured in the field. Such values normally are associated with direct strokes, no indications of which had been found.

Since it was believed that voltage drop in the ground connection between arrester and secondary neutral might account for the measured voltages, an investigation of this factor was made in 1935. The results, shown in part in figure 4, indicated that in 21 out of 27 measurements voltage drops up to 16 or 18 kv occurred. In a few records there was an apparent rise in voltage between arrester and transformer, as shown, for example, in the first record for location 23. Omitting these records, the voltage drop in the 7 to 10 feet of leads conducting surge current to ground averaged 0.73 kv per foot. Several values of 1 kv per foot and 2 values of about 1.7 kv per foot were indicated.

These data show that even where interconnected arrester and transformer are installed on the same pole, the surge voltage appearing at the transformer may exceed the arrester voltage considerably unless the arrester leads are short. With arrester and transformer on separate poles, the advantages of the interconnection are partially nullified.

At one location, several abnormally high voltages were measured directly across an arrester of a type with normal breakdown voltage of about 16 kv, which was confirmed by subsequent tests on this arrester (table III). The reason for the high measured voltages is not known. Aside from this particular location, the voltage measured *directly* across the lightning arrester at locations of interconnections in no case exceeded 22 kv, whereas several records obtained at transformers with normal arrester protection showed voltages between primary phase and secondary neutral of 40 kv or more.

Table III—Breakdown Voltages of Arresters Removed From Surge Recorder Locations; Effect of Wave Front

Location	Arrester: Make or Type	Arrester: Mfr's. Approximate Value of Surge Breakdown Voltage, Kv	Voltage Recorded in Service, Kv, Primary Phase to: Separate Ground	Voltage Recorded in Service, Kv, Primary Phase to: Secondary Neutral	Surge Breakdown Voltage (Kv) of Individual Arresters for 3 Rates of Rise (Kv per μsec): 20 to 25	50	150 to 160
22	*A*	15	43.6	37	15.0	16.7	22.1
20	*B*	15	47	37	16.1	16.9	24.9
23	*B*	15	39.2	28	16.4	18.1	23.1
18	*C*	15 to 17	43.6 49.5 73.5	30* 30* 37*	16.2	18.2	18.8
8	*D***	13	78	33	15.8	16.5	16.5

* These voltages were measured directly across the arrester terminals; the measurements at the other locations included several feet of leads.
** Arrester without series gap. Impedance drop voltages are given.

Cable Poles. In one measurement, with normal arrester protection, a voltage of 33 kv from primary phase to separate ground subjected the cable insulation to 30 kv. In another case, where the lightning arrester ground lead, secondary neutral main, and cable sheath were interconnected, with a 41 kv surge on the primary phase wire the voltage on the cable insulation was only 11 kv.

Long Circuits. Voltages recorded on 2 long circuits confirmed the previous conclusions regarding the limited development of traveling waves on such circuits. The extension of measurements on one circuit in 1934 to cover a distance of approximately $^2/_3$ mile made it possible to obtain 2 sets of records which indicate that surges of this length may exist on long distribution circuits. One of these sets of measurements showed surge voltages of approximately 500 kv to ground about 350 feet on each side of an arrester location at which the voltage on the primary phase wire was only 140 kv. At this location a neutral arrester was shattered, confirming the previous conclusion that in general whenever voltages of 400 or 500 kv occur, equipment damage usually results.

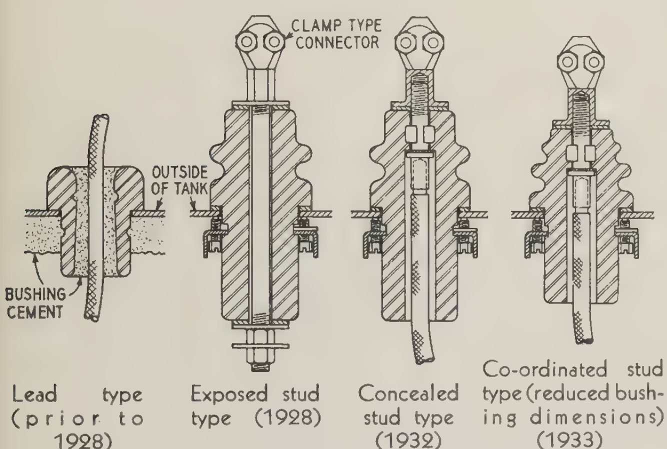

Fig. 5. Principal stages in the development of distribution transformer bushings used in Chicago

The bushings shown are primary bushings; secondary bushings are similar, except that co-ordination usually is effected by arcing horns or lugs

Arrester Discharge Currents. Several records of surge currents through arresters were obtained by means of magnetic links, concurrently with voltage records, at surge voltage recorder installations in 1935, as shown in figures 3 and 4. In none of these cases were the arresters damaged. The currents measured in these and the 300 other links ranged from 500 amperes in a number of cases to about 8,000 amperes in 3 cases.

Transformers With Stud Type of Bushings

Beginning in 1928, practically all distribution transformers purchased by the Commonwealth Edison Company have had stud type bushings.[7] Figure 5 shows chronologically the principal steps in the development of bushings for distribution transformers.

Table IV—6 Year Data on New Lead and Exposed Stud Types of Transformers

Item		(A) Lead Type		(B) Exposed Stud Type		Ratio B/A
Transformer-years of service		20,200	....	20,000		0.99
Annual rate of burnout due to lightning, per cent	Coils	0.069	(14)	0.035	(7)	0.51
	Leads	0.050	(10)	0.035	(7)	0.70
	Total	0.119	(24)	0.070	(14)	0.59
Annual rate of fuse blowings due to lightning, per cent		0.223	(45)	0.700	(140)	3.14
Annual rate of total troubles due to lightning, per cent		0.342	(69)	0.770	(154)	2.25
Estimated annual hours of outage due to all lightning troubles		115	....	237		2.06

Note: The numbers of transformers burned out and fuses blown are shown in parentheses.

The results of a statistical study of lightning troubles on 2 control groups of transformers having lead type and exposed stud type bushings, respectively, are given in table IV. To eliminate the age variable, new transformers in each group were selected and their operating records followed for several years. This investigation indicated that with the exposed stud type of transformers, protection of the windings was obtained at the expense of fuse blowings. The high rate of fuse blowings appears to be attributable to low bushing flashover voltages as compared with the combined strength of the bushings and heavy lead insulation of new lead type transformers.

Few winding failures of stud type transformers have occurred in Chicago. It is believed that longer life will result for the newer transformers with co-ordinated electrical design because of better insulating materials, provisions for improved oil circulation, and conservative loading conditions. Insulation deterioration resulting from lack of attention to these factors in the past probably has contributed to transformer troubles primarily assigned to lightning.

A 2 year statistical study of the comparative effect of the *interconnection* in reducing fuse blowings caused by lightning on lead and stud type of transformers showed that the reduction for lead type of transformers of all ages resulting from the interconnection was 73 per cent, whereas that for relatively new exposed stud type of transformers was only 38 per cent. While a large part of this difference may be accounted for by the differences in ages of the 2 types studied, it must be ascribed partly to the newer method of terminating leads from the winding in a stud type of bushing having a low impulse ratio as compared with that of the insulation and compound surrounding relatively new leads.

Improvements in Design. Data on lightning troubles for the few transformers of the *co-ordinated* stud type installed on the Chicago system are as yet insufficient to permit a statistical analysis of their performance. It is expected that failures caused by lightning will be more infrequent than for earlier designs, but, because of lowered bushing arcing distances, slightly higher rates of fuse blowings may be anticipated. Consideration therefore was given to

possible improvements for future distribution transformers.

The results of the surge voltage recorder measurements, showing lowered tank potentials, indicated that a reduction in bushing flashovers and fuse blowings could be effected through the use of a low voltage gap across the secondary neutral bushing, thereby limiting the drop in tank potential to the breakdown voltage of this gap. This modification recently has been included in specifications for distribution transformers for Chicago, a $^1/_4$ inch gap, having a sparkover voltage of 10 to 15 kv on a $1^1/_2$x40 microsecond surge, being selected as the minimum practicable spacing.

An additional factor of assurance against fuse blowings probably can be obtained by increasing the flashover voltage of the primary bushings. An increase of the same magnitude as the decrease in the secondary neutral bushing flashover voltage would have little effect on insulation co-ordination, yet should prevent flashover from occurring in some borderline cases where, for example, the lightning arrester may be too far from the transformer to limit lightning voltages sufficiently. This situation applies, for example, to some transformers on the Chicago system.

Where the transformer tank normally is grounded, best performance from a lightning protection standpoint may be expected where the tank is grounded directly to the secondary neutral wire at the transformer, even if a separate pole ground is provided.

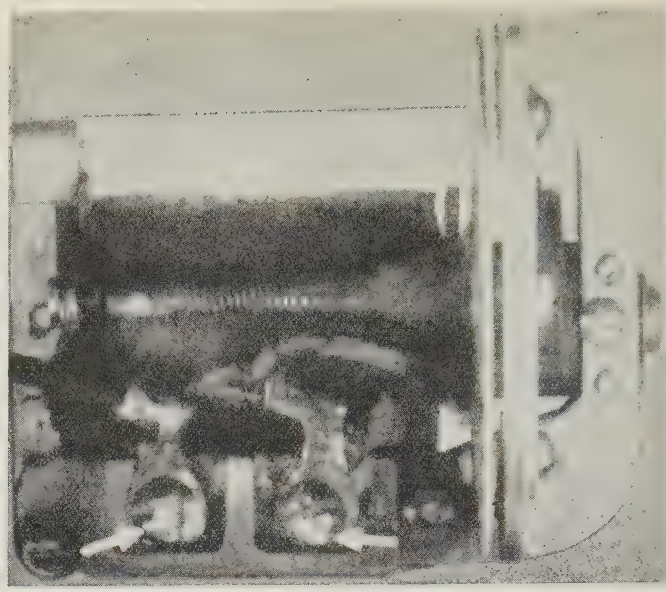

Fig. 6. Typical examples of damage to watt-hour meters by lightning

Arrows indicate burn marks
Motor of demand register (above)
Lighting meter (left)

The proposed methods of grounding tanks are advocated irrespective of the type of arrester protection employed.

Watt-Hour Meter Burnouts

Over a 4-year period, an average of 350 failures were caused annually by lightning among the 988,000 watt-hour meters in Chicago. About 270 of these involved demand registers, which alone had a failure rate of 45 times that of light and power meters. This high rate appears to be attributable to fusing of the fine wire used for coils and leads by surge currents and to unusually small clearances at the demand motors.

Failures of light and power meters generally involve only internal leads. It appears that the surge flashover provides a path for subsequent follow of power current: The burning and pitting of terminals and case (figure 6) in numerous instances seem too severe to be solely the result of surge energy. Clearances between leads or terminals and case as small as $^1/_{16}$ inch were found on some of the older meters, as compared with clearances of as much as $^3/_8$ to $^5/_8$ inch on some newer types.

An investigation in 1935 indicated that arrester interconnection increased the rate of meter burnouts by roughly 25 per cent. In view of the low rate of such troubles, this increase is far more than offset by the reduction in transformer troubles and improved service resulting from the interconnection. Furthermore, while in the course of this investigation more than 400 meter burnouts were caused by lightning, only 16 cases of lightning damage to customers' wiring, fuses, or other inside equipment were reported; and these indicated no higher rate of troubles with the interconnection than with normal arrester protection.

Arrester Protection for Underground Cables

Not more than 2 failures of cables connected to overhead lines have been caused by lightning each year in Chicago. Early in 1935, therefore, it was decided to make a trial removal of arresters from about 250 cable poles equipped with air-break potheads where additional arrester protection at transformers on the same phase wires was provided within 500 feet, and where the connected underground cable was at least 2,000 feet in length. Calculations made on the basis of traveling wave theory indicated that under the specified conditions surge voltages would be reduced sufficiently by the arrester installed within 500 feet of the cable pole to prevent lightning damage to the cable insulation, which has impulse strengths of 200 to 300 kv. The surge breakdown voltage of the cable joints presented an unknown factor, but only one joint failure had been caused by lightning in the preceding 10 years.

The results of this trial removal during one lightning season apparently confirm the analysis, since no failures of cables or joints caused by lightning occurred. The several hundred arresters made available were placed in stock for use elsewhere on the system.

Lightning Arrester Deterioration and Tests

Routine Tests. Beginning in 1933, all lightning arresters removed from service which appear to be in good condition have been tested before being returned to the stockroom. In lieu of surge tests, for which equipment was not available, the following 60 cycle tests were devised and found practicable for 3 kv arresters:

1. With operating voltage of 2,300 volts impressed across the arrester, the leakage current in microamperes (effective) is measured. The maximum allowable leakage current is set at 150 microamperes except for one type of arrester with no series gap.

2. The 60 cycle effective value of breakdown voltage is determined in relation to normal values for new arresters. The minimum and maximum allowable breakdown voltages are 3 kv and 10 kv, respectively, except for 2 types of arresters for which an upper limit of 15 kv is set. Arresters are rejected also if the breakdown is very gradual or if the arrester has high resistance after breakdown.

After arresters found in poor external mechanical condition had been rejected, 1,845 arresters were tested over a 3 year period; 85 per cent was found to be satisfactory electrically. The remainder was rejected for the following reasons: excessive leakage current, 10 per cent; high breakdown voltage, $4^1/_2$ per cent; low breakdown voltage, $^1/_2$ per cent. Some arresters were rejected for unsatisfactory breakdown action, but in practically all cases these arresters had also excessive leakage current.

Arrester Deterioration. Recently, in order to obtain a check on the limiting value of leakage current employed in these routine tests, 77 arresters of various types which had been rejected mainly because of excessive leakage current were broken open and examined. As illustrated by the typical group of arrester parts shown in figure 7, varying degrees of corrosion caused by moisture entering the arrester were found.

A careful correlation of the measured 60 cycle leakage currents of these arresters before examination with the approximate degree of corrosion of the gap assemblies confirmed the test method as well as the value of leakage current

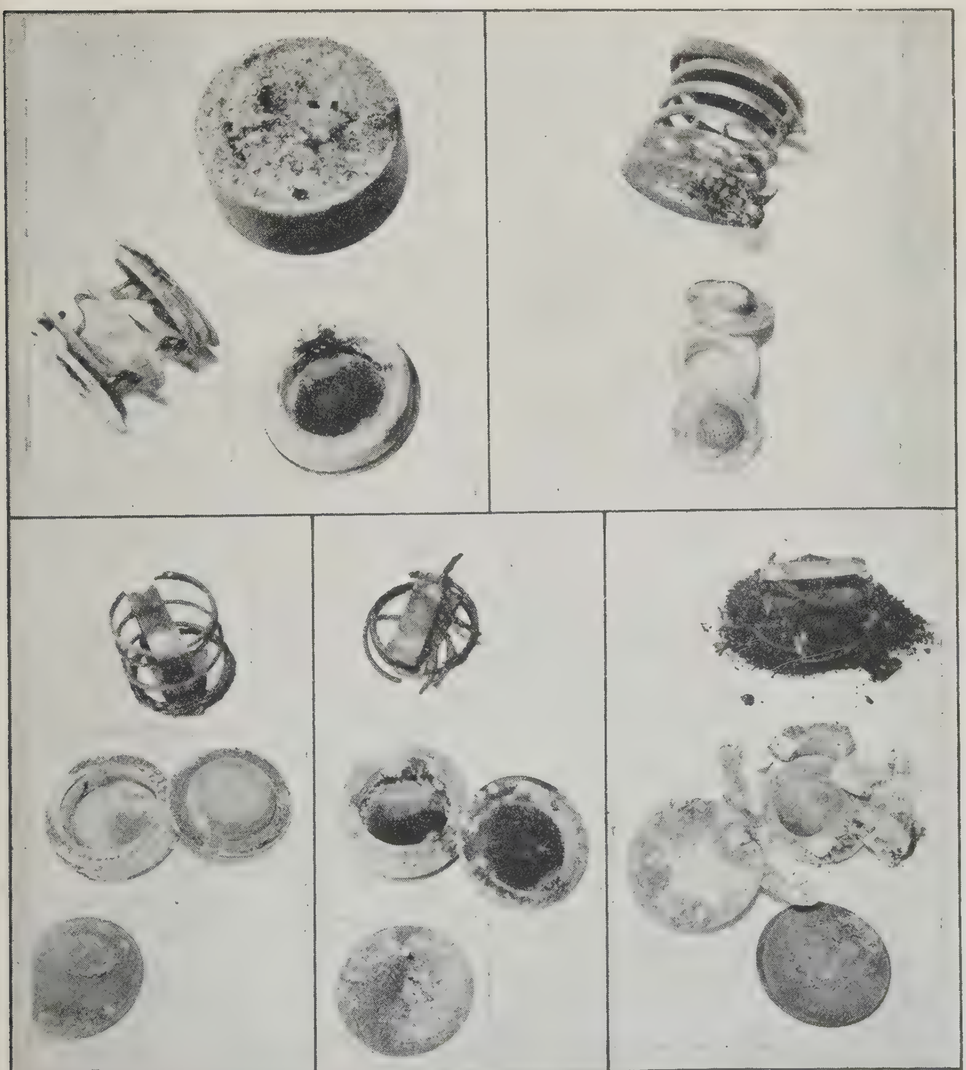

Fig. 7. Corroded lightning arrester parts found on dissection

The lower group shows, from left to right, progressive stages of corrosion on 3 arresters of one type

employed as a basis of rejection. It was found that with the limit of 150 microamperes no arresters in satisfactory condition were rejected, and all arresters with "corroded," "badly corroded," or "very badly corroded" gaps, and about $^2/_3$ of those with "slightly corroded" gaps were rejected.

The following reasons for high breakdown voltages were found upon dissection of some arresters: (*a*) gap electrodes burned away; (*b*) complete destruction of internal parts of arrester in service; or (*c*) damage to the characteristic or resistance material.

On the basis of these results, which confirm similar investigations made prior to the adoption of this method of test, it appears that inexpensive 60 cycle tests may be employed with a fair degree of accuracy to determine the serviceability of used distribution arresters. This method appears applicable also to the testing of arresters in service. While a-c testing cannot be considered a full substitute for surge tests, it may be used with some assurance to detect internal changes in the arrester.

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Supervisory Control and Remote Metering

Supervisory control and remote metering installations on the electrified section of the Pennsylvania Railroad are outlined herein. A brief history of the growth of electrification on this railroad, and of the supervisory control and remote metering installations which accompanied the electrification is given, together with the locations at which the different types of equipment are used. These remote metering and control systems have been of considerable assistance in load dispatching and substation operation.

By
J. V. B. DUER
FELLOW A.I.E.E.

Pennsylvania Railroad, Philadelphia

THE use of supervisory control and telemetering on the 11,000 volt a-c electrified service of the Pennsylvania Railroad has been brought about through a gradual evolution as the territory in which electric trains are operated has expanded. The railroad has not yet adopted the policy of performing all actual switching operations of substations and trolley circuits from a central point. As a matter of fact, a busy railroad has a distinct advantage which precludes the necessity for such a means of operation. This advantage is that the railroad provides itself with trained men at each interlocking point who perform the remote operation of the track switches.

These men are capable and can readily be qualified to operate the control board for an adjacent substation and such a switchboard can usually be installed in the signal tower where the operator is located. This procedure has been adopted in the operation of all of the electrically controlled power switching for electric traction in the past and has been continued up to the present with a few notable exceptions.

Early Electrification and Supervisory Control Installations

At this point a brief résumé of the growth of the electrically operated portion of the railroad (see figure 1) should be of interest to bring out the necessary refinements in the method of operation and supervision of the power system.

The first 11,000 volt a-c overhead catenary electric train operation on the Pennsylvania Railroad was put in service in 1915 between Philadelphia and Paoli. This installation had one power supply point, a synchronous condenser station, and 3 substations on a line 20 miles in length. The substations were controlled by interlocking tower operators under the telephone supervision of a "power director" located at West Philadelphia. This installation was enlarged to include the branch to Chestnut Hill in 1918. A 2 phase feed was installed at the power supply point and 2 substations were built.

The first step in the through electrification project between New York and Washington was inaugurated

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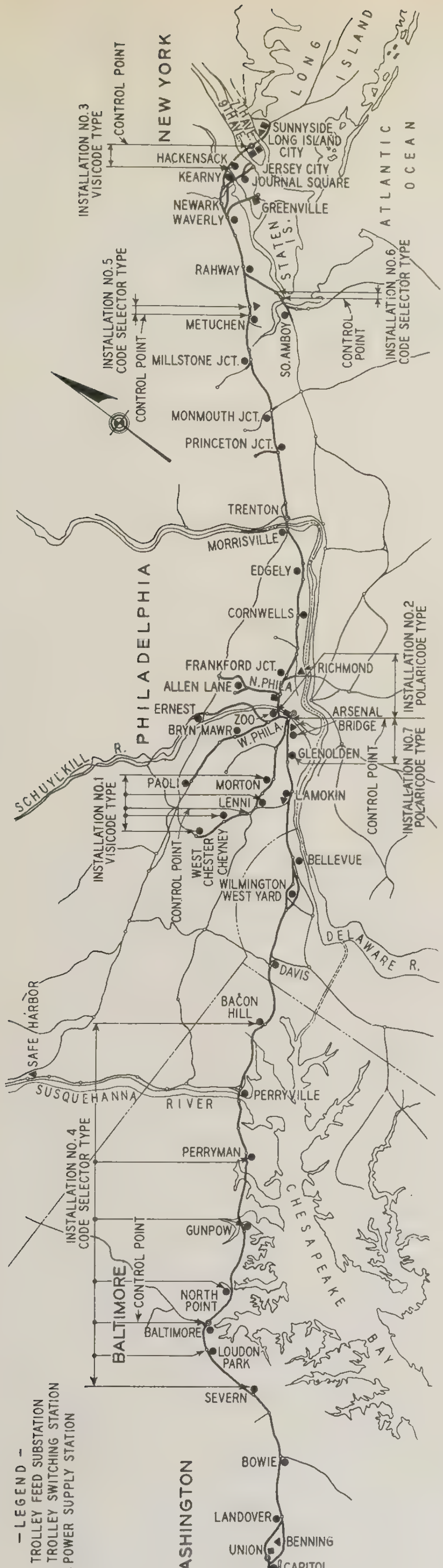

Fig. 1. Map showing substations and power supply points and location of supervisory control installations

between Philadelphia and Wilmington in September 1928. This installation was made with 132,000 volt transmission to fit in with the through service plans. Five substations were built and a new power supply source was provided.

Later in 1928 the branch to West Chester was placed in operation. Here for the first time supervisory control was considered desirable and was installed. On this branch there is only one interlocking tower which is manned for the full 24 hour period. It thus became desirable to concentrate the control of the 4 substations on the branch at this tower. The extreme substations are $17^1/_2$ miles apart so that supervisory control was necessary. The original installation was of the 4 wire "synchronous visual" type. In this case the line wires were run in aerial cable and were subjected to severe induction conditions. Tests made in 1930 indicated that a change was necessary in the equipment in order to minimize the effect of the induced voltages. The equipment was then changed to the 2 wire "visicode" type with suitable drainage devices. (See reference 1 at end of paper.) This change eliminated the troubles, and the installation is now giving satisfactory service. A list of the supervisory control installations of this railroad is given in table I.

Inductive Co-ordination Problems

Generally, the use of supervisory control in conjunction with an a-c railroad electrification is attended with more than the average problems in inductive co-ordination. These problems are in common with the inductive co-ordination of the railroad's communication circuits since the supervisory control wires are usually in the same cables. The principal factors which aid in controlling induction are: (*a*) substantial construction and insulation of the power circuits to reduce the frequency of occurrence of faults; (*b*) use of high speed relaying and circuit breakers to limit the duration of faults; (*c*) thorough bonding of rails and installation of ground wires to reduce earth currents; and (*d*) the installation close to the communication cables of shielding or neutralizing wires bonded to the return circuits.

In spite of these steps calculations have indicated in some locations that the line wires will be subjected to 440 or 550 volts to ground maximum induced potential due to heavy load currents and to even higher potentials due to short circuit currents. It is thus necessary to design the equipment to withstand these voltages. If it is desired to permit the operation of the equipment under these conditions, drainage equipment is installed to hold the induced potentials to a value below the breakdown point of protectors which may be installed in the line wires.

Electrification and Supervisory Control Extended

In 1930 the main line between Philadelphia and Trenton was completed for electric service, as was also the branch to Norristown. This project included the building of 6 more substations. At this time the electrified territory was divided into 2

operating zones, each with a separate "power director," and at the same time a second installation of supervisory control was made. Only one substation was involved. This substation is known as Zoo (*D*-1) substation. It is now the largest trolley substation on the electrification, and serves as the principal supply for the incoming trackage and the yards in the Philadelphia terminal area. At this substation, also, are the 132 kv oil circuit breakers for sectionalizing the transmission lines.

When the substation was put in service there was no nearby permanent interlocking tower large enough to handle the control board. Direct electrical control to the Philadelphia power director's office was considered but proved uneconomical and too bulky compared with the telephone type of equipment used on supervisory control. Supervisory control was, therefore, installed. The synchronous visual type was used. This installation operates over a comparatively short line and the cable is not run close to trolley contact circuits. No trouble has been experienced with induction and the installation has given good service.

During the past year the substation has been enlarged, and the power director's office from which it is controlled has been relocated. This required considerable work on the supervisory control equipment. Thus, at the manufacturer's suggestion, the opportunity was used to convert the equipment to the new "polaricode" type. The high speed of this equipment has proved a distinct advantage for this substation, which has over 100 points of control and supervision.

In 1933 electric train service was inaugurated between Philadelphia and New York. This meant the addition of 12 more substations and switching stations and 2 more power supply stations. Three new power director's zones were established, one of which was a consolidation with the d-c third rail operation between New York and Manhattan Transfer. As the d-c third rail operation was changed over to a-c overhead catenary operation it became possible to close the d-c substation at the Hackensack, N. J., portals of the tunnels under the Hudson River. Since the operator of this substation also operated the control board for the adjoining a-c service transformer substation another means of control for the a-c station had to be provided, as well as remote operation for the 3-phase 11,000-volt line circuit breakers in the d-c station which are still required to supply the transmission feeders to Newark for the Hudson and Manhattan service out of Jersey City. It was decided to use supervisory control operated from the power director's office in New York. The visicode type of equipment was installed similar to that used on the branch to West Chester.

Finally, in 1935, now that the entire project between New York and Washington has been put into service, there are a total of 40 trolley transformer stations and 8 trolley feeder switching stations. Power supply is obtained from 7 separate supply points. The entire distribution system is divided into 7 separate zones each supervised by a power director. The power supply and 132,000 volt transmission system has been placed under the direction of a system "load dispatcher" located in Philadelphia.

Spacing of Substations

At the time the project between Wilmington and Washington was laid out it was found that a considerable economic advantage could be obtained in spacing the substations without giving primary consideration to the proximity of a suitable control point. It then

Table I—Supervisory Control Installations on the Pennsylvania Railroad Electrification

Installation No. on Fig. 1	Apparatus Controlled	Location of Dispatching Office	Type	Wires Required in Normal Operation	Spare Wires	Can Spare Wires Be Put in Service by Dispatcher?	Metering Wires	Units Controlled and Supervised	Units Supervised Only	Units Metered	Distance From Dispatcher's Office to Substation—Miles
1	Morton substation	Wawa interlocking tower	"Visicode"	2	2	No	Direct over separate wires	15	2		8.1
1	Lenni substation	Wawa interlocking tower	"Visicode"	2	2	No	Ditto	29	4		0.7
1	Cheyney substation	Wawa interlocking tower	"Visicode"	2	2	No	Ditto	6	2		4.1
1	West Chester substation	Wawa interlocking tower	"Visicode"	2	2	No	Ditto	15	2		9.4
2	Zoo substation	Office of Phila. pwr. dir.	"Polaricode"	4	4	No	Ditto	92	14		1.5
3	Hackensack substation	Office of New York pwr. dir.	"Visicode"	2	2	No	2	58	2	14	3.0
4	Bacon Hill substation	Office of Baltimore pwr. dir.	"Code selector"	2	2	Yes	2	29	3	8	47.1
4	Perryman substation	Office of Baltimore pwr. dir.	"Code selector"	2	Same pair as above	Yes	Same pair as above	26	3	8	26.4
4	Gunpow substation	Office of Baltimore pwr. dir.	"Code selector"	2	Same pair as above	Yes	Same pair as above	27	3	8	16.2
4	North Point substation	Office of Baltimore pwr. dir.	"Code selector"	2	Same pair as above	Yes	Same pair as above	38	12	10	5.6
4	Loudon Park substation	Officeof Baltimore pwr. dir.	"Code selector"	2	2	Yes	2	36	13	10	4.6
4	Severn substation	Office of Baltimore pwr. dir.	"Code selector"	2	Same pair as above	Yes	Same pair as above	28	3	8	14.1
5	Metuchen switching structure	"HU" interlocking tower	"Code selector"	2	None			4			1.1
6	Trolley sectionalizing switches	"WC" interlocking tower	"Code selector"	2	None			4			1.5
7	Glenolden substation	Office of Phila. pwr. dir.	"Polaricode"	2	2	No	Control wires used	27	3	8	6.8

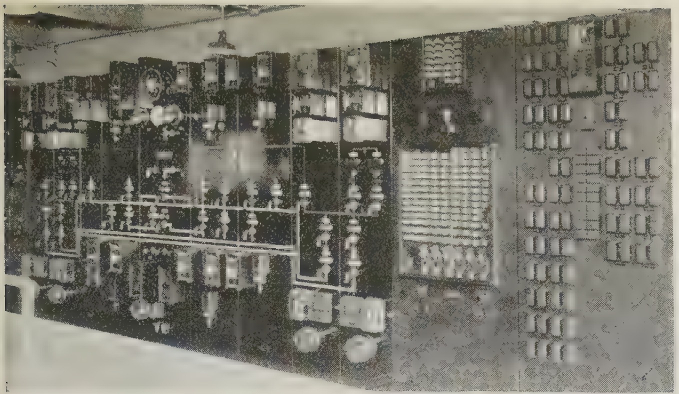

Fig. 2. Relay board in North Point substation, Baltimore

The 2 relay panels for the code selector type supervisory control are on the right

became economically feasible to place 6 of the 12 trolley transformer substations between Wilmington and Washington under the direct supervision of the power directors in Baltimore by means of supervisory control. (See figure 2.) The substation in Baltimore station itself has its direct electrical control operated from the same point. Thus, in this area, a large amount of the switching operations are performed by the power directors themselves, without need of recourse to the intermediate step of telephone instructions to interlocking tower operators. This installation controlled from Baltimore is the most extensive installation of supervisory control on the Pennsylvania Railroad, both in respect to number of points controlled and distances over which the control is operated. The "code selector" type of equipment is used with drainage tuned to reduce 25 cycle induction, and the operation has thus far proved quite satisfactory.

Other Supervisory Control Installations

As the steam train service has been eliminated it has been found possible to close many of the facilities provided for that service. This condition made desirable one further installation of supervisory control. The substation involved is at Glenolden, Pa., and was formerly controlled by the operator of a water-pumping station nearby. The polaricode type of equipment has now been installed for this substation controlled from the Philadelphia power director's office. (See figure 3.)

At the present time, of the 40 trolley transformer substations in service in the electrified territory, 13 are operated by supervisory control and the remaining 27 are operated by remote electrical control.

In addition to the operation of principal substations by supervisory control 2 other minor installations are in service. One installation controls 4 132,000-volt line horn-gap switches which tie in the supply from the Metuchen power supply station to the through transmission lines. These switches were at first hand-operated, but the need for remote operation soon became apparent. No convenient control point being available, a simple 5-point code-selector type of supervisory control was installed, operated from Metuchen interlocking tower.

One other installation was made of 5-point code-selector supervisory control. In this instance, 4 switches again were involved. These switches are used to sectionalize the trolley circuits in Perth Amboy. The need for remote electrical operation was apparent, but the nearest suitable control point was so located to make this type of control impracticable. Hence, supervisory control was again used operated from Perth Amboy interlocking tower.

Remote Metering

In all of the cases in which supervisory control is used to operate a trolley transformer substation a certain amount of remote metering is also required. The customary procedure when remote electrical control is used to operate a substation is to furnish the interlocking tower operator with meters giving him the following indications:

Trolley bus voltage.
Substation battery voltage.
Current in each power transformer.
Signal power generator voltage.
Signal feeder voltage.
Signal power generator current.

When the supervisory control system is comparatively short, it is perfectly feasible to obtain voltage readings over direct wire by means of a high resistance voltmeter, and this has been done. A-c readings of current and voltage, over long runs, are obtained by means of standard rectified current telemetering. When a separate pair of metering wires is provided, any one metering indication can be read continuously without interfering with the normal operation of the supervisory control system. This arrangement has been provided in the case of the 6 substations operated from Baltimore. When this latter installation was under consideration, the number of control wires to be used was given considerable

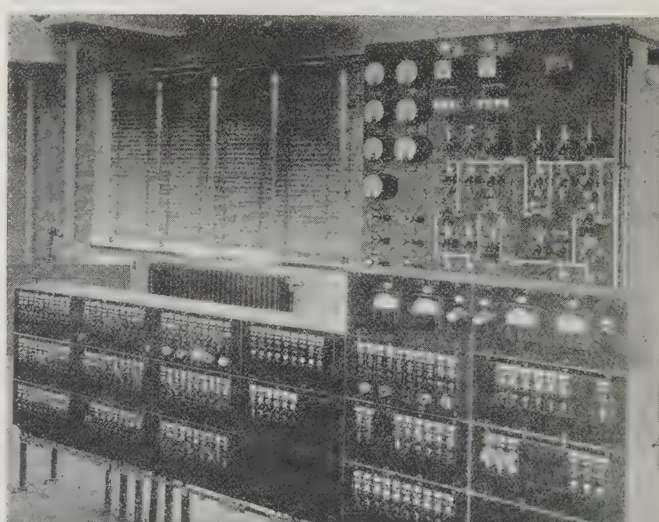

Fig. 3. Supervisory control boards in Philadelphia power director's office for Glenolden and Zoo substations

study. On account of the importance of the substations a separate pair for each substation is used for control and one single pair north and south of Baltimore is used to provide the metering indications for all substations. This was felt to be a logical use of the available wires at the same time providing maximum availability of the control circuits at all times.

From the foregoing it can be seen that the only remote metering indications received in conjunction with the supervisory control systems are those which would obtain if the supervisory control were not used, and these indications are received by the operator charged with the direct responsibility of controlling the substation involved.

Conditions Recorded by Remote Metering

In the general supervision of the transmission lines and power supplies, the system load dispatcher must be furnished with prompt and accurate information of all switching changes, load swings, and availability of equipment at the substations and power supply stations. Most of this information reaches him by means of direct telephone communication with the power directors and the operators at the supply stations. However, load swings, the division of load between supply stations, and the interchange of power between the principal sections of the railroad are constantly changing, so that for a large system it becomes impracticable to follow these conditions by telephone. Since these conditions have a vital effect upon any switching operations on the transmission lines and on the starting up or shutting down of generators a continuous record of such conditions is most necessary.

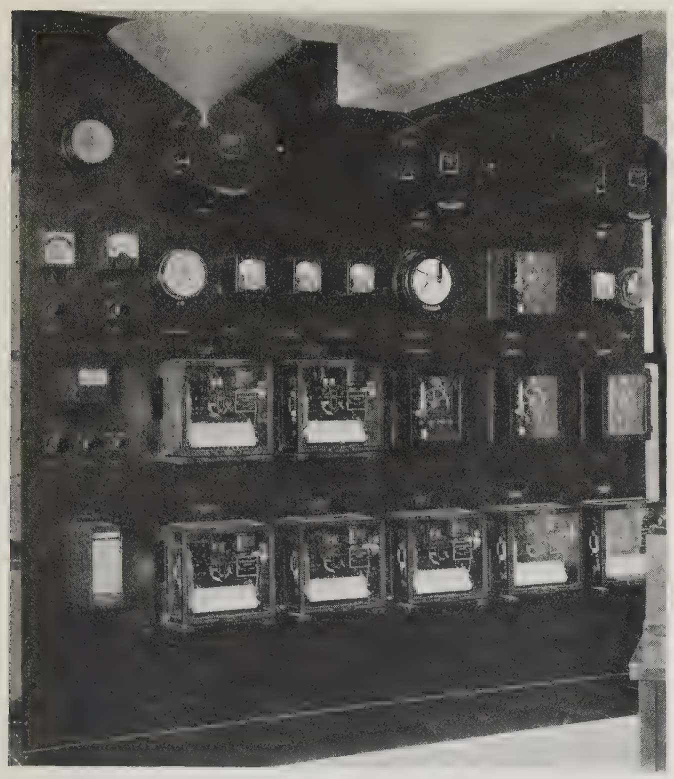

Fig. 4. Individual telemetering recorders for each power supply point, and associated watt-hour meters and system demand meters

This recording equipment is located in the system load dispatcher's office

Fig. 5. View of part of system load dispatcher's office

Total load telemetering recorders are located directly in front of the dispatcher's desk

With this in mind a complete power supply and interchange telemetering system was laid out and installed, providing recorders and demand meters in the load dispatcher's office in Philadelphia.

Purchased power is furnished under 2 contracts, one including the territory north of the Susquehanna River at Perryville, and the other including the territory south of Perryville. The transmission circuits normally are operated as a continuous line between New York and Washington, so that power interchange metering also is required at Perryville for both active and reactive power.

The telemetering indication of output kilowatts is brought over a pair of telephone wires from each power supply point direct to recorders in the load dispatcher's office. (See figure 4.) For the shorter runs, thermal converter transmitters are used transmitting a proportional d-c voltage. For the longer runs, thermal converters and boosters or torque-balance telemeters are used, transmitting a proportional direct current. The current system instead of the voltage system is used on the longer runs in order to minimize the effect of induced voltages.

The recorders at the dispatcher's office are of the self-balancing potentiometer type. A total of 11 is used, 1 for each of the 7 power supply stations, 1 for the total on the northern contract, 1 for the total on the southern contract, 1 for active power interchange at Perryville, and 1 for the reactive power interchange. In addition to this, by means of a special circuit arrangement energy is totalized for each contract and for the interchange. (See figure 5.) The hourly demands are indicated and recorded by means of conventional type demand meters.

This telemetering system has proved to be a valuable adjunct to the load dispatcher's office and has

demonstrated an accuracy which is entirely practicable for proper supervision of the power supply to the electrification.

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Modernization of Power Distribution Systems

Engineering and practice in electric power distribution systems have kept pace with modern developments in other lines. Many improvements in system design and in details of equipment and construction have been produced in recent years which make for economy, better service, greater safety, and better appearance. The most important of these are discussed with indications of future trends.

By
H. P. SEELYE
MEMBER A.I.E.E.

The Detroit (Mich.) Edison Company

THE distribution system for electric power supply offers a fertile field for "modernization." It is characteristic of distribution that its earlier practices grew largely from "practical" solutions of the problem of getting service to the customers, rather than from careful engineering study. The present widespread interest in distribution costs indicates a recognition of the large amount of capital tied up in the distribution system and the opportunities for improvement and economy. Unfortunately, the idea seems to be somewhat prevalent that distribution engineering has been backward and that improvements in distribution are to be looked for in some radical changes which are "just around the corner." On the contrary, it is fair to say that distribution engineering has kept pace with engineering in other lines, and that any system can be thoroughly modernized by practices now available which have been well tried out by some of the industry. Future improvements are to be expected, of course, but major changes of a revolutionary character are not to be anticipated, at least in the near future. This paper will discuss some of the modern phases of distribution, first in a general sense, then with reference to systems for serving loads of different density, and finally some of the more important details of equipment and construction.

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Measure of Modernization

In order to define the limits of this discussion a measure of the term "modernization" is desirable. Whereas the word "modern" is sometimes applied to anything which is new and different, it is believed that in this case the idea of "style" should be excluded and the meaning should comprehend some more substantial advantage. There are 4 purposes which should be served by modernization—it should result either in better service, lower cost, greater safety, or better appearance. The best modern design should accomplish all 4 if possible, but at least one of them should be served if a change is to be justified. Modernization in some cases includes the idea of rebuilding. The present discussion should not be limited by that, however, since frequently the possibility of rebuilding depends upon the age of the equipment, and must be deferred until depreciation makes a change economical. The attributes of a modern distribution system will be presented without regard to their application to new or rebuilt construction.

Service Requirements

As a basis for the design of distribution it is necessary to consider the requirements of the service to be rendered. In general, a continual increase in the load density and energy consumption is to be expected for some time to come. The possibilities offered by a widespread use of the larger appliances such as ranges and water heaters together with the normal increase in small appliances, refrigerators, air conditioning, etc., indicate that loads in residential districts may be expected to grow in some places to densities several times those now common, with appreciable increase in load factor. Since the growth over the whole system will not be uniform, however, it is to be expected that even greater variation in loads will be experienced than now exists and it will be very difficult to prophesy just what growth will be likely in any specific area. This points to the desirability of having a system which is as flexible as possible, that is, one which will be economical over as wide a range of loads as feasible, with a minimum of rebuilding.

The quality of service which is demanded is also rising. As customers become accustomed to good voltage regulation, freedom from flicker, and infrequent outages they tend to become less tolerant of inferior conditions. Furthermore, if electrical serv-

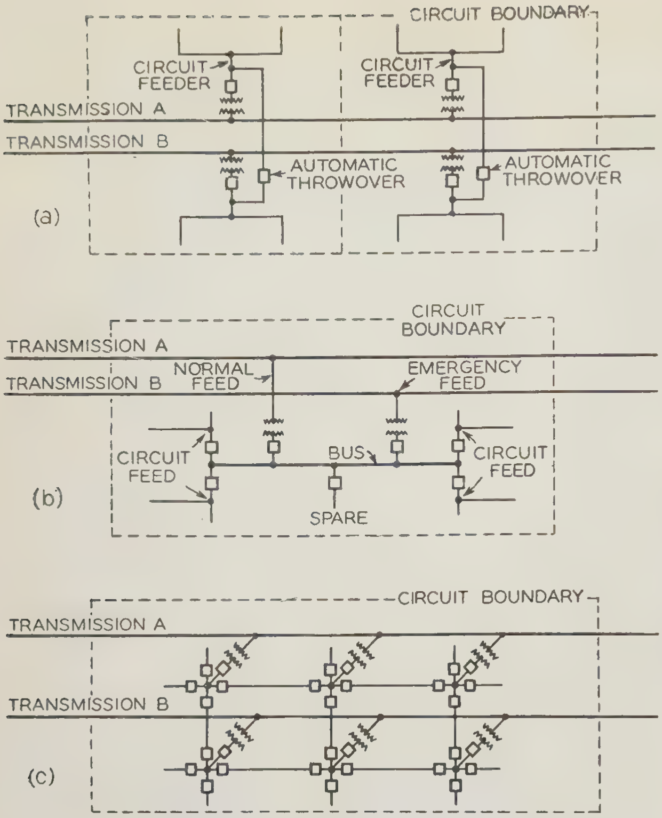

Fig. 1. Different arrangements with small substations

a—Paired circuits *b*—5-position station *c*—Primary network

ice is to replace other facilities in such important functions of life as cooking, refrigeration, and heating it must have at least as good quality and reliability as the facilities replaced. Even on farm lines, where a high degree of reliability is difficult, such operations as milking, incubation, and soil heating will not endure long outages. One of the most serious problems of the distribution engineer is how to supply a sufficiently good quality of service to meet the needs of modern use without spending more than can be justified by the financial return.

Substation Size and Arrangement

The first of the specific features of a distribution system to be considered is the size and arrangement of substations. The present trend seems to be toward a relatively small size of substation feeding the load by a few short circuit-feeders rather than large substations with numerous circuit-feeders of various lengths. Several comparative studies covering specific situations which have been published have indicated that this arrangement has an economic advantage.[1–5] In general, the reasons for this are:

1. When the outgoing feeders are few and of about the same length, it is feasible to use bus regulation by means of automatic tap changing equipment in the transformers. This is cheaper than regulation by individual, induction type, feeder regulators.

2. Reduction in major outages due to use of shorter feeders.

3. The small station allows station capacity to be increased by smaller steps as the load grows, thus saving in investment charges.

4. The small station makes a more flexible system, since it can be installed more quickly when required, and moved more readily if load conditions change.

5. Some advantage in loading of transmission lines is claimed due to the better average loading on the smaller increments of station capacity, the transmission line being branched to pick up several stations. Also, if the transmission is interleaved, less reserve capacity is sometimes feasible, although this is not always possible on account of field conditions and methods of operation.

Just how small the substation should be is a question which probably can be answered only by a careful study of location conditions. The answer will no doubt vary considerably for different systems.

Fig. 2. Small unit substation, Altoona, Pa.

One limitation might be the size necessary to avoid voltage dips from large motors or welding apparatus.

Of several possible arrangements, other than the simple single units supplying one or more circuits radially, 3 are shown in figure 1. Figure 1*a* indicates a unit consisting of 2 transformers, each supplied from a separate transmission line and each serving one or more circuits, with an automatic throwover between them for emergency. Figure 1*b* is a station with 4 operating circuit positions and 1 spare, the supply being normally from transmission line *A* with emergency throwover to transmission line *B*. The total firm capacity of such a station would run from perhaps 1,000 or 2,000 kva to 8,000 kva depending upon the size of the circuits.

Primary Network

One application of the small substation, which has been used to some extent, and which has done a great deal in calling attention to the advantages of such units, is the so-called primary network.[5,6] In this scheme, each substation unit consists of 1 transformer with 4 circuits feeding out in different directions (see figure 1*c*). Each circuit is tied in to a circuit feeding from another station unit which is connected to a different transmission line. If several transmission lines can be interleaved satisfactorily, the reserve capacity necessary in lines and station units may be somewhat less than with the schemes previously described. The fact that the circuit feeders are all tied together into a continuous network for operation may sometimes be an advantage in maintaining better voltage but may also prove to be a disadvantage in making the control of the loading on any unit more difficult and, if the

1. For all numbered references see list at end of paper.

system is ungrounded, making it harder to locate grounds. Basically, the 3 schemes which have been suggested are not so very different and the best one to fit any local conditions may be chosen by a study of relative costs as applied to the peculiarities of the system in question.

Unit Type Station

The development of the unit type substation has accompanied the trend toward the smaller station.[6] In general this consists of an outdoor-type transformer with automatic tap-changing equipment, and with the necessary circuit breakers, wiring, and auxiliary equipment all enclosed in weatherproof steel housings. The unit is mounted on a concrete mat or, if the housings are suitable for submersion, it may be placed in an underground vault. Various combinations of equipment are possible. Such an installation unquestionably makes for neatness and good appearance, as is apparent from figure 2, and has been used in several cities apparently with satisfactory results. Some companies, however, prefer to provide permanent shelter for operators and repairmen and for tools and other miscellaneous equipment. A small station building housing the circuit breakers and other equipment and also providing for these facilities is an alternative to the outdoor unit which is probably not widely different in cost.

Heavy Density Distribution—A-C Network

The a-c secondary network has been quite generally accepted as the modern method of serving high density load such as is found in the downtown districts of the larger cities. A great deal has been written about this scheme of distribution so that not much needs to be said here regarding its characteristics or details except that it has proved to offer a satisfactorily reliable service for these loads for which the d-c network was formerly considered necessary. Considering secondaries only, the a-c network is naturally a more expensive form of distribution than a radial system and hence its application should be limited to conditions where the service requirements warrant it. In some cases, however, an over-all economy has been obtained by the use of networks with primaries of the higher voltages, such as 13 kv or 26 kv, for which radial operation was not considered feasible, and by which intermediate substations could be eliminated. In general the criterion for a network will be the ability of the customers served to endure outages of the frequency and duration which may be expected with the type of primaries and secondaries to be used. For very heavy densities and important loads this may indicate a network regardless of the type of lines. For lighter densities where occasional short outages may not be considered serious, the necessity for using underground primaries might be the deciding factor. Wherever, on account of congestion of structures, magnitude of voltage, restrictions against overhead lines, appearance, or any other similar reason it is necessary to resort to underground lines for primary feeders, it is usually necessary, in order to give a high quality of service, to provide means for automatically maintaining service in case of failure of one of such lines, since underground lines require a relatively long time to repair. The extension of the use of networks into medium density areas in which overhead lines can be maintained is sometimes prophesied, but it is hard to see how this can be justified, for some time to come at least, in view of the quality of service which it is possible to give with radially supplied overhead lines.

A fairly recent development is the overhead type of network protector and transformer which allows the transformer and secondaries to remain overhead while the primaries are underground. This has a very useful application in areas where a complete underground network is anticipated, but where it is still possible to maintain pole lines, as on the fringes of a heavy-density network area. The cost of such an installation is appreciably less than one in an underground vault. In Detroit this scheme is being used throughout an area in which d-c service has been given but where a parallel a-c network is planned to take new load and gradually assume the old load. The transformer installations are as shown in figure 3. In most cases both underground and overhead secondaries are supplied from the same transformer, as required by the load and by the necessary tie capacity.

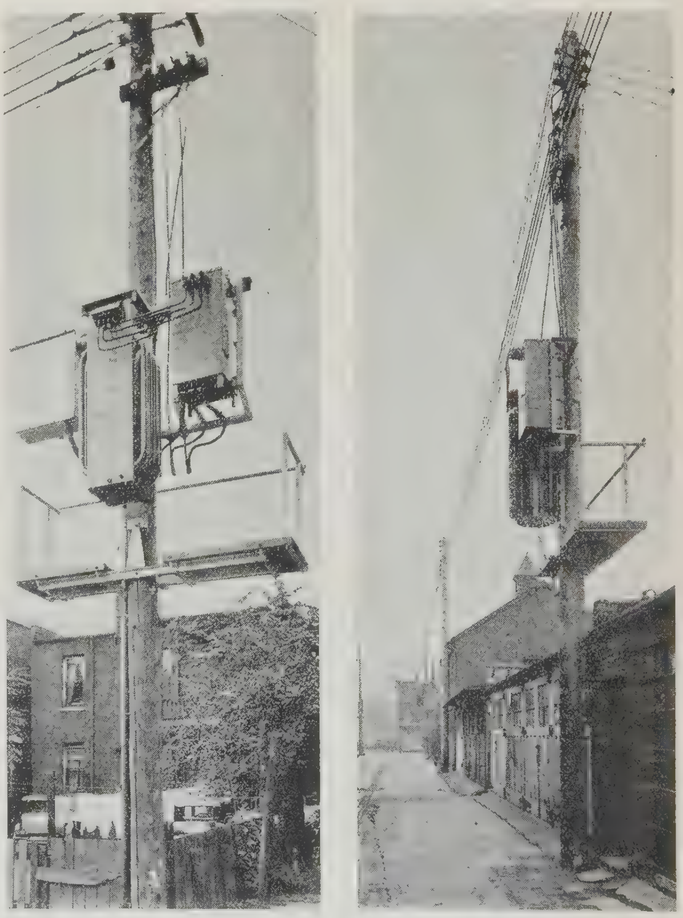

Fig. 3. Overhead network transformer installations in Detroit

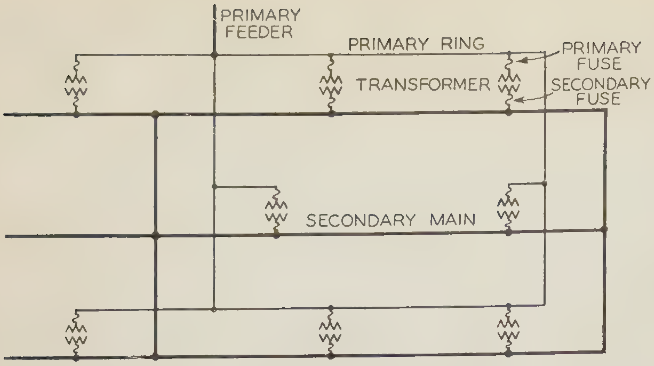

Fig. 4. Diagram of secondary bank

Medium Density Distribution—Secondary Bank

For medium-density areas such as the residential areas of towns and cities, where overhead lines can be maintained, the secondary bank scheme is receiving considerable attention. This scheme is not new, having been used for many years in some cities, notably Detroit. The secondaries of several transformers are tied together, the transformer being protected by fuses on both primary and secondary sides, as in figure 4. A faulty transformer is thereby cleared from the system, leaving the secondary supplied from the other transformers in the bank. An essential part of the scheme is that the primaries be tied in rings rather than merely radial branches. The combination of these arrangements gives a high degree of reliability, and has the further advantage of maintaining better average voltage and of reducing voltage dips along the secondary, since unusually heavy loads, such as motor starting currents, are divided between at least 2 transformers.

A definite comparison of the reliability of the secondary bank scheme with that of radial distribution is very difficult to make since other characteristics of any 2 systems are always somewhat different. One year's record (1931) for 220 circuits in Detroit on a 4,800 volt ungrounded system, serving about 185,000 kva, with 12,000 single-phase transformers, indicated that out of 480 cases of primary fuses blown or wires down, which might have been expected to cause some interruption with a radial system, the banked secondaries and ringed primaries prevented or limited to one minute or less 424 cases and in 49 other cases reduced the extent of the interruption.

The ultimate reliability of the secondary bank scheme is sometimes questioned on account of the possibility of the whole bank "cascading" due to a fault on the secondaries or in a transformer, blowing the fuses on all the transformers in succession before the fault is cleared. It is true that careful designing of the system is necessary to prevent this occurrence and even then it will happen occasionally. The record of fuse blowing and bank failures in Detroit for a year will be interesting as an indication of what might be expected. There were quite a number of such cases involving only 2 or 3 transformers, as might be expected since these cannot be considered to constitute a satisfactory bank. There were 11 cases affecting 4 or more transformers and in all of these only 1 side of the secondary was out of service, the other side remaining intact. A comparison of the total amount of service interruption actually experienced, with what would probably have been interrupted with a radial system indicated that there would have been about 5 times as much with the latter. Even with 2-transformer banks only, the radial system still showed nearly 2 times as much interruption. While 2-transformer banks are not to be recommended if larger ones are possible, this record indicates that they are still to be preferred to individual transformers from the standpoint of service reliability. Incidentally, this same analysis indicated a decided advantage, on the whole, for the "solid bank" scheme, with the secondary fuses in the transformer leads, over the "loose bank" scheme with the secondary fuses mid-way between transformers, although for the small banks there was comparatively little difference.

Size of Secondary and Transformers

It has been shown by careful studies of comparative cost by The Detroit Edison Company and others that a moderate size of wire with medium sized transformers is appreciably cheaper for ordinary distributed loading than large wire and large transformers.[7] In general, number 4 to number 2 wire seems to be the most suitable for load densities now encountered or to be expected for some time to come. From a standpoint of cost only, the smaller sizes usually show to advantage but when other factors, such as voltage dip, unequal distribution of load, and possible load growth are taken into account, a somewhat larger size may be advisable. In figure 5 is shown a typical series of curves giving comparative costs of different wire sizes at various load densities, assuming a $2^1/_2$ per cent maximum voltage drop and with a limit placed on voltage dip. The Detroit Edison standard, which has been based upon such a study with consideration also given to a widespread use of electric ranges, with their fairly large concentrated loads, calls for number 2 secondary with transformers of the required size spaced about 700 to 800 feet apart. Some modifications of this are, of course, necessary in such cases as heavy commercial

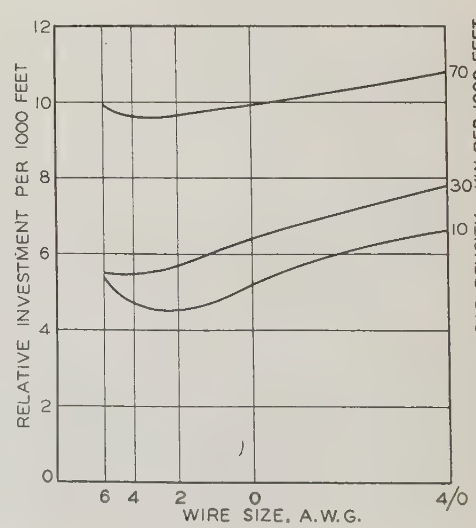

Fig. 5. Comparative costs of secondary distribution, based upon $2^1/_2$ per cent voltage regulation and limited voltage drop

or concentrated loads which require larger wire, or very light density where larger transformer spacing is suitable, but the standard is quite generally followed for ordinary average urban distribution.

Scattered Load—Farm Lines

Perhaps the most outstanding new development in distribution construction in the past few years has been the long-span farm line for extending service into light-density rural territory. Prior to about 10 years ago such rural lines as were built followed, for the most part, the precedents set by urban construction, using weatherproof wire and fairly heavy poles spaced about 150 to 175 feet apart. Such construction was heavier than necessary for the conditions and hence more costly. The increasing demand for electrical service at a moderate price in rural territory stimulated the development of a type of line, based upon engineering design, which would be as cheap as possible, and yet be adequate mechanically and electrically for the requirements of the territory. Bare conductors have become available which have the necessary conductivity and yet have higher mechanical strength than the copper, notably steel-reinforced aluminum and copperweld-copper. These allow poles to be spaced out to 400 feet or more without using excessive sags. Light poles, class 6 or 7, have been found adequate from both the theoretical and practical standpoints. The details of construction have been simplified as far as possible. Further economy has been found in some localities by the use of straight right-of-way off the roads and clear of trees, thereby avoiding high poles, corners, and angles with their guying, and future maintenance due to tree interference. The result of all this has been a very appreciable reduction in cost of such lines, to less than half of the cost of the previous type in some cases. The Detroit Edison standard farm line, which is typical of this development and of which about 2,500 miles have been built, is shown in figure 6. It uses number 2 aluminum-cable steel-reinforced (ACSR) conductor, and class 7 pine poles at 400 foot spans, with a small separate transformer, in most cases at every customer.

Fig. 6. Standard farm line of the Detroit Edison Company

Underground Farm Lines

A very recent innovation in farm line construction has been the introduction of a special underground cable for this purpose. This cable is designed for single phase lines with one side grounded, such as a 2,300 volt branch from a 4,000 volt line. In one type, the grounded conductor consists of a spirally wrapped, soldered, copper tape, which also constitutes the waterproof sheath, being itself protected by an outer fibrous covering. It is laid directly in the ground with a special plow. Although there is little conclusive data on its actual average cost or reliability, it seems to offer promise of being a suitable construction, especially for locations where right-of-way is difficult and overhead lines relatively costly. Such underground lines have the advantages and disadvantages of other underground lines in being not subject to lightning and storm troubles, but requiring special provision to be made for restoring service in a reasonable time if a fault does occur. It seems unlikely that an underground line can be built which will be as cheap as an equivalent overhead line under favorable conditions, but there are probably many situations in which a low cost underground line can be justified. In this connection it has been pointed out that where the primary feeder is of one of the higher voltages, such as 13,200 volt, the use of low voltage (2,300 volt) branches may be more economical, even with the necessary step-down transformers, on account of the lower cost of equipment, particularly distribution transformers, fuse cutouts, and lightning arresters.[8]

Details of Construction and Equipment

Of the infinite number of details of construction and equipment which enter into a modern distribution system, space will permit only mention of a few which are particularly new or are of especial importance. These will be discussed briefly.

Poles

There has been, in general, a tendency in the past to use poles which were stronger than necessary for the loads to be carried. Within recent years an

"American Standard" classification of poles has been set up which allots a definite strength rating to 7 specific classes, with corresponding dimensions for any species of timber. This classification has been quite generally accepted and allows poles to be purchased which will fit closely the design requirements. Furthermore, experience and tests have shown that excessive strengths are not necessary for reliability if proper attention is paid to the original design, to the depth of setting, and to maintenance. Whereas class 2 or class 3 poles are quite commonly used in some cities for distribution lines, others find class 5 or class 6 satisfactory. Similarly, farm lines are frequently built with poles as large as class 4, whereas others, under similar conditions, use class 7. Modernization for economy points to the future use of poles which are not stronger than necessary.

The use of treated poles is so general that little need be said about it. The fact that a well treated pole will last at least from 5 to 10 years longer than an untreated one should make it obvious that the relatively small increase in price is an economy in almost all cases except purely temporary construction.

Conductors

Bare Wire. The fact that the weatherproof covering on wires constitutes very nearly 30 per cent of the total weight, and hence of the total cost, for wires number 0 and smaller, points to the economy in using bare wire wherever feasible. The modern long span farm line uses bare wire for primaries and in some places it has been installed for secondaries as well, although the trend is away from the use of secondaries on such lines. There has been considerable interest lately in the idea of extending the use of bare wire into urban districts also, on the basis that the weatherproofing has little insulating value, except when new and dry, and might just as well be eliminated. While this may be true for outlying districts, this practice should be approached with some caution for congested urban territory on account of the possible increase in outages. A great deal of foreign material is thrown across the wires in city districts, kite strings, fine wire and even larger objects. While weatherproofing is not an adequate insulation, it does offer some protection against outages due to this cause for voltages 5,000 volts or lower. In Detroit, 4,000 pieces of scrap material, which did not cause outages but were potential sources of trouble, were removed from the lines in one year. It would seem advisable from this standpoint to look for a better covering than the present standard weatherproofing for congested districts and use bare wire in outlying territory where the trouble from foreign material is not so prevalent. One or 2 conductor coverings are now being offered which give promise of being considerably better insulation than weatherproofing at not a large increase in cost. An increase in the spacing between wires is also a means of reducing outages from such cases where comparatively close spacing has been customary.

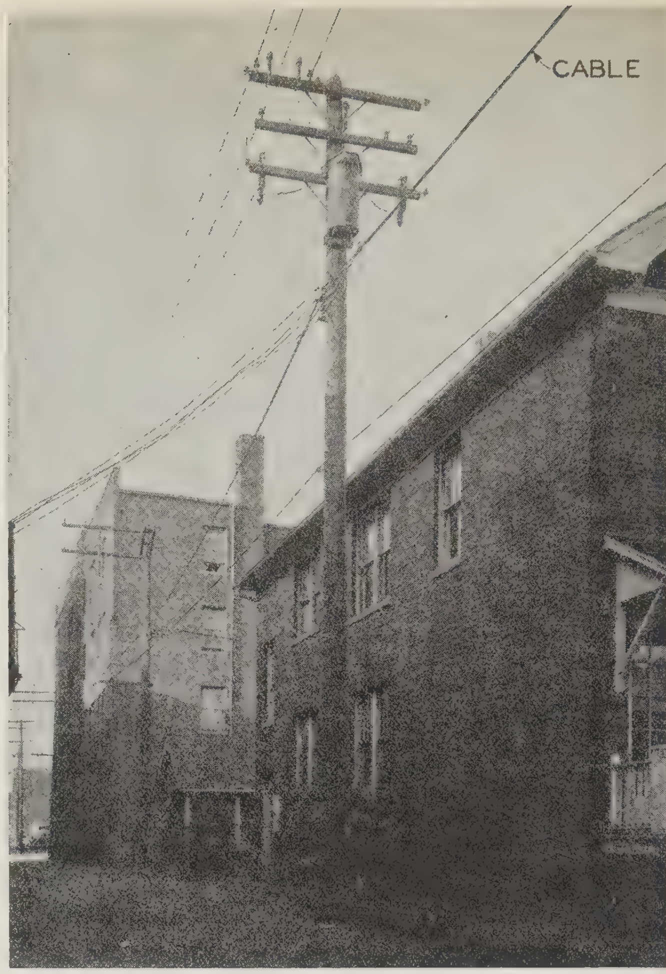

Fig. 7. Cabled secondary, as used in Detroit

Overhead Cable. Overhead cable for primary circuits has been used in some places. This has the advantages of avoiding most of the troubles due to trees, storms, and foreign material and makes an improvement in appearance at a less cost than underground construction. It is subject to the same disadvantage as underground cable, however, in requiring a relatively long time to locate and repair faults, and hence requires similar provisions for restoring service quickly.

Cabled Secondaries. A form of overhead cable for secondaries has been used to a small extent in Detroit in locations where a close spacing of conductors was desired to reduce the circuit inductance. (See figure 7.) This was built up in the field with individual insulated wires for the phase conductors, supported on a bare messenger which was also the neutral. This is an economical and convenient construction for the purpose.

Long Spans in Cities. Long spans of 250 feet or so have been suggested for city use, services being taken off by flying taps at mid-span. This is predicated on the savings to be accomplished by the use of fewer poles. While the practice may be suitable for some cases, it is believed that, in general, where services are taken off frequently along the line, it will be found that the extra costs involved in high strength messenger, guying, additional pole

strength, and inconvenience in construction and maintenance will more than offset the savings on poles.

Transformers

Impedance. There has been a tendency recently to demand considerably lower impedance for distribution transformers than has previously prevailed. This has been actuated largely by the desire to reduced voltage dips, and hence flicker in illumination, and also to allow greater overloading on short-peak loads. There are limits to which this can be carried economically and it has been pointed out that about $2^1/_2$ per cent impedance is as low as can be justified for small transformers.[9] It may be anticipated that some such value will eventually be generally adopted, probably grading up to something like $3^1/_2$ per cent for the larger sizes—in fact such transformers are now available in certain types such as the 4,800 volt transformers being bought under The Detroit Edison specifications. It is very desirable that a common standard table of impedances be agreed upon. If further reduction is found necessary in certain cases it can probably be better obtained by using oversize transformers than by attempting to lower the general characteristics. The use of secondary banks is another means of counteracting voltage dips which is somewhat more effective than the lowering of transformer impedance, since it lowers the drop on the secondaries as well as in the transformers. Another means which has been found useful where transformer locations are somewhat limited and fixed is the use of small autotransformers out on the secondary to balance 115 volt starting currents across the 230 volt circuit.

Loading. Considerable economy can be obtained in the modern system by taking means to insure that transformers are loaded as fully as possible. It is not uncommon to find average loadings less than 50 per cent of the transformer rating. If advantage is taken of the inherent overload capacity of transformers under the short-peak loads, which are characteristic of most of the residential and small commercial distribution, and of secondary banking to distribute the loading more equally, it is possible to increase this materially. In Detroit it has been demonstrated that it is possible to obtain an average on all single phase transformers of 75 per cent or more in built-up territory and even of 100 per cent on some circuits. Since the difference between 40 per cent and 100 per cent loading represents a difference in investment of about \$8 to \$10 per kilovolt-ampere of load, such measures are well worth while. Naturally, a higher per cent loading requires more careful attention to load determination by periodic testing in order to avoid trouble from overloading.

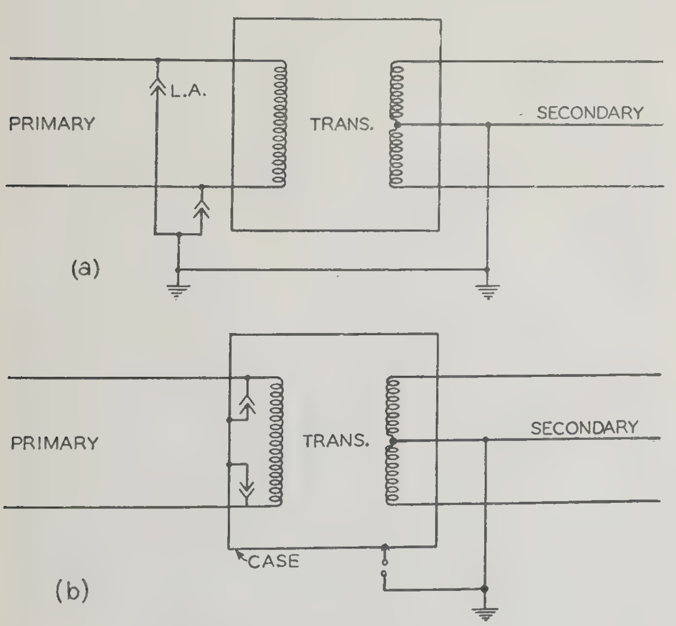

Fig. 8. Interconnection of grounds at transformer

a—External lightning arresters *b*—"Surgeproof" transformer

Lightning Protection. The economy of providing lightning protection in the form of an arrester at each transformer has been quite well established. Formerly the ground connection of the arrester was kept separate from that on the secondary neutral. In recent years the practice of interconnecting these ground connections has been demonstrated to be effective in reducing transformer failures and the service interruptions due to blown fuses. By this arrangement (see figure 8) the voltage applied across a transformer's windings during the discharge of a surge is limited to that across the arrester, regardless of the additional voltage which is necessary to pass the surge over the impedance of the ground connection. If the transformer windings are insulated so that they can withstand the arrester voltage, failure is prevented. Modern transformers are being built with the insulation designed for this purpose. In some cases auxiliary gaps across the primary bushings are added to protect the windings further when the surge discharged is of such high energy that the arrester voltage is abnormally high. Transformers are available with the lightning arresters inside the case, also with arresters in the primary entrance bushings.[10,11] Some operators prefer to use separate arresters, however, so that an arrester failure will not affect the transformer and also so that the lightning discharge will not pass through the primary fuses. There are several variations of the interconnection described, the transformer case being included in the ground connection in some, and case, neutral, and arrester ground being separated by small gaps in others, but the principle is much the same. Experience has shown, in general, about a 60 per cent reduction in transformer failures and an even greater reduction in fuse blowings when interconnection was introduced with present transformers, although these figures vary in different localities.[12]

Self-Protecting Transformer. A type of transformer is being offered as being completely self protecting. In addition to lightning arresters inside the case, a circuit breaker on the secondary side is also included for overload and short circuit protection. Since the only duty remaining for a primary fuse is to remove the transformer in case of faults due to defective windings, leads, or bushings, this

fuse is incorporated as a simple link fuse under oil in the primary connections to the windings. This arrangement has the advantage of giving a completely self-contained unit, requiring no auxiliary apparatus for its use. It has not yet had enough years of actual operating experience to prove conclusively whether or not it will give as good ultimate reliability as the older type of fuse-arrester-transformer combination.

Farm Line Transformers. Considerable interest has been evidenced lately in a new type of transformer designed particularly for economy in use on farm lines. The various features are reduced to as simple a form as possible—one primary bushing mounted in the cover, the other grounded side being connected to a stud in the tank, 3 secondary terminals, or possibly only 2, with the neutral of the secondary being connected inside to a stud in the tank. In some cases it is intended to use no fuses and no lightning arrester except a gap set to protect the windings, it being expected that these transformers will be used in conjunction with reclosing sectionalizing fuses or circuit breakers on the line. These will interrupt the whole branch in case of a fault or lightning discharge which does not clear, but will restore service if the fault is only temporary. This equipment is too new to allow any conclusions to be drawn as to its ultimate practicability or actual economy.

Regulators

The increasing demand for better voltage regulation on the modern system has led to more attention being paid to the automatic regulation of individual circuits. The induction regulator, which is a comparatively expensive apparatus, has been the accepted means for this purpose, where its cost could be justified. Where lines were so long that something more was needed to keep the voltage up at the end, boosters have been sometimes inserted, but these have the disadvantage of boosting the voltage at light loads as well as heavy. Recently, a line of step-type regulators has been produced which seems to offer a good solution to many of these problems. These range in size and design from those suitable for substation use, with a series of small steps, giving results somewhat comparable to the smooth curve of the induction regulators, down to a simple, one-step, automatic boost for use on branches where the considerable voltage change will not be objectionable. It seems likely that this equipment will be used quite extensively as loads grow and better service is required.

Services

The modern trend is decidedly toward the use of outdoor metering. The so-called "new sequence" which allows the meter to be placed ahead of the service switch, stimulated this. The chief advantages are, quite obviously, the facilitation of meter reading and inspection and the reduction of current diversion. Socket type meters are available for mounting the meter directly, or boxes in which the older type of meter may be enclosed are also in use.

During the past year or so there have been quite extensive trials made of the use of concentric type service cable for the service drop from the pole to the house and down to the meter. (See figure 9.) This cable has usually been made with the grounded neutral conductor in the form of strands spiralled around the insulated 115 volt conductor, or conductors, the whole being covered by a weatherproof braid, with or without a protective taping of paper or fabric tape over the conductor. While such an installation presents a neater appearance than the open-wire service drop, it costs somewhat more. Its value in preventing current diversion is somewhat questionable as probably the greater part of such prevention is accomplished when the meter is placed outdoors. The cable on the house itself will usually cost less than the older type of service entrance using rigid conduit. The use of concentric cable adds to the possibilities of troubles due to short circuited services if the insulation between the conductors is not fully adequate for the conditions imposed, since the conductors are in close proximity for the whole length and protected only by the insulation and fibrous covering. Although rubber insulated conductors have been used to some extent for outdoor service for many years, there is still considerable question as to just what type of compound and of outside covering is necessary for long

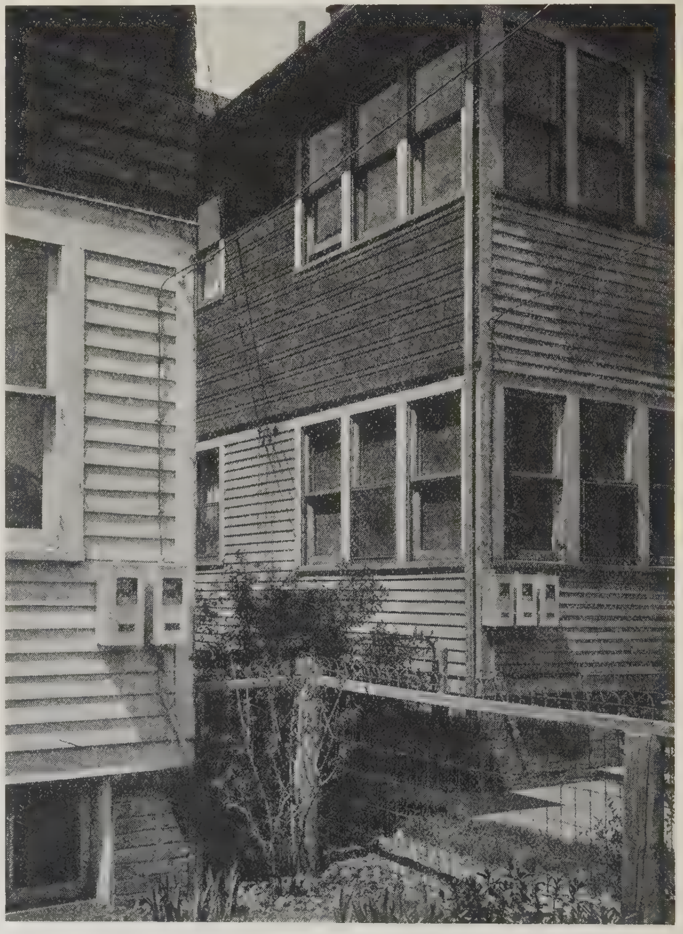

Fig. 9. Service with concentric service cable and outdoor meter

Fig. 10. New style distribution construction for better appearance

service under sunlight and other varying weather conditions. If considerable trouble is to be avoided, precaution should be taken in using these cables that the quality is such that they may reasonably be expected to give such service.

Appearance

It is fair to say that the appearance of overhead lines has been quite largely disregarded in the past. Overhead lines have been considered as necessary evils which at best are no ornaments, so it wasn't worth while to give much attention to making them look better as long as the construction was reasonably neat and workmanlike. The only alternative, where better appearance was actually demanded, was to remove the lines entirely, placing them underground. When the large difference in cost between overhead and underground lines is considered, however, it is evident that an appreciable amount of additional expenditure can be justified in improving the appearance of overhead lines if the change to underground can be thereby forestalled.

There are any number of examples in any city of structures which have been subjected to ornamental design in order to make a virtue of a necessity, and at least to remove objections to their unsightliness. Chimneys, water towers, ornamental street lamp posts, and, going back to first principles, even the exteriors of residences and commercial buildings, have been architecturally designed so as to be interesting and decorative rather than merely utilitarian. Even advertising signs have been changing character in that direction under pressure of public opinion. There is no basic reason why overhead power lines cannot be similarly treated from an architectural standpoint. It is quite likely that sooner or later this step in modernization will be taken.

There are 3 steps in improving the appearance of the lines. The first is the reduction in congestion of the pole leads by simplification of the system and by placing the more important through circuits underground. The second step is in cleaning up the leads by doing away with unnecessary materials and spare wire positions, making the design as compact as possible; also, the placing of leads in locations off the main streets and roads, where they will be as inconspicuous as possible, is included. The third step, which has had little attention as yet, is the redesign of the structures, using different shapes and arrangements for the component materials, in order to introduce some architectural coherence and elements of ornamentation. A step in this direction is shown in figure 10, which is a radically different construction that is being tried out by The Detroit Edison Company. Further details may be found in reference 13. The changes made have not introduced additional cost. No attempt at ornamentation was attempted, but only the introduction of a more pleasing configuration. Some such design is specially suitable for residential districts, whereas for commercial and industrial areas, present types of construction may be more suitable if made as neat and unobtrusive as possible by the application of the first 2 steps mentioned.

Engineering and Standards

The most important element in the modernization of a distribution system is an adequate and competent engineering staff. It is not always recognized that the problems in distribution are many and complex and, for satisfactory solution, must have the careful attention of engineers who are technically trained and also have a background of experience and good engineering judgment. The amount of money invested in distribution and the economies and improvements possible, as indicated in this paper, warrant such attention.

Even if the engineering work is of the highest caliber, there still exists the problem of insuring that it is properly carried out in field practice. Distribution construction is so widespread and requires so many variations to meet specific conditions that it is very difficult to control it closely. It is essential that complete and definite standards for materials and structures be set up and enforced if the intended results are actually to be accomplished. A well engineered set of simplified standards will effect appreciable economy over construction which is merely built by each construction crew to meet what the occasion demands. The Detroit Edi-

son Company has found it worth while to have line construction specifications which are complete to considerable detail. See reference 14. These are kept up to date by continuous attention and revision and are enforced as strictly as possible. Materials are completely standardized as far as this company's own organization is concerned and are nearly all bought under written specifications and subject to careful inspection upon receipt. By these means the type and quality of construction is controlled to follow the best that the engineering can produce.

Summary

It is believed that the conclusion can be drawn from the foregoing discussion that distribution engineering has been diligent in keeping abreast with modern service requirements. The amount and quality of service demanded have been increasing and will probably continue to increase. The truly modern distribution system in both its general scheme and in its details has a flexibility which allows it to accommodate a wide range of loads with relatively small changes and yet do so with economy. It offers a service which is as free from interruptions and of as good voltage regulation as is required by the type of load carried, and foresees a general tightening of these requirements, and yet does not include excessive investment for a quality which is not really necessary. It takes account of the appearance of its structures, that they be as unobtrusive and unobjectionable as is practicable while retaining the obvious economy of overhead lines. In general, the modern distribution system is so designed and constructed that "energy may be transmitted to the customer at the least possible cost consistent with good service."

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Lightning Arrester Economics

Early applications of lightning arresters were hindered not only by high cost, but also by the general lack of knowledge of both the characteristics of lightning and the protective characteristics of the arresters themselves. Present knowledge of these factors, however, achieved as a result of extensive field and laboratory research, has made possible the production of arresters having greatly improved characteristics and at much lower costs, which has led to their extensive use for protecting transformers and other equipment. This paper presents a brief review of the history of lightning arresters, and discusses factors affecting their economic application to electric power systems.

By

PHILIP SPORN
FELLOW A.I.E.E

I. W. GROSS
ASSOCIATE A.I.E.E.

Both of the American Gas and Electric Co., New York, N. Y.

LIGHTNING ARRESTER economics is no different from any other economics encountered either in the engineering field or in the everyday business world. It is the old problem of balancing total cost against total savings. The cost of an arrester and its carrying charges must be considered in relation to items of greater damage to equipment, loss of service, incidental hazards, and sometimes greater cost of equipment, where lightning arresters are not used. The problem is easily stated but not so readily solved, mainly because the fundamental and necessary data have been altogether too scarce and sketchy to make possible even an approximate solution.

In this paper are given a brief résumé of the hectic early history of the arrester, reference to its more mature growth (particularly in recent years), statistical data on actual service performance of arresters on distribution and high voltage systems, a discussion of the factors affecting the economic application of arresters, and an evaluation of some of these factors.

A paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 28–31, 1936. Manuscript submitted Nov. 6, 1935; released for publication Nov. 30, 1935.

1. For all numbered references see list at end of paper.

Early Life and Development of the Lightning Arrester

For a long time knowledge of the lightning arrester and its application were considered to belong exclusively to a special esoteric group. The average engineer thought, in fact, was made to think, that he had to install a lightning arrester whenever he was dealing with a high voltage circuit and that if he did he was safe. That expected safety did not always materialize; but if equipment failed in spite of the installation of lightning arresters, there were always 2 alibis. First, a "surge" was said to have occurred on the system. If that explanation did not suffice, then the trouble could be explained as having been caused by the good old dependable "direct stroke." Until quite recently, this second alibi has been repeated with a frequency not at all warranted by its intrinsic merit as a true explanation of apparatus and equipment failure under lightning conditions.

With the present knowledge of the lightning arrester and lightning phenomena, it is interesting to go back some 20 years and review the literature that has been written on the subject. In 1914 Nicholson said,[1] "Frequently the question is asked—Are they efficient? Are they necessary? We operating people reply by saying, 'Yes, they are necessary if you think so, the result being, most of us are afraid to leave them off.'" In the same year Steinmetz wrote,[1] "..... it occasionally happens that even a good lightning arrester fails to protect the coils of transformers. These failures mean merely that when we speak of lightning we do not know the nature of the surge ....." The practice at that time is well brought out by a committee report[2] which shows, of 23 companies reporting, 19 used arresters, 3 used horn gaps and resistors, and one used no arresters. This record confirms the first citation, "most of us are afraid to leave them off."

While theory can give the basis for the design and application of a protective device, only the results of actual experience truly can confirm a practice. In this connection a committee report[3] in 1921 shows the pessimistic attitude among the operators. One company said, "Past experience with lightning arresters makes it difficult, if not impossible, to justify their expense, particularly so at the higher voltages. Another said, "We finally, in 1912, stopped using them entirely, and our expense of maintenance has materially reduced." In the same report is found, "Our experience with arresters (since 1910), however, soon demonstrated that it would be a cheaper thing to have spare transformers than ...... to repair the ...... arresters. We probably pay some penalty in first cost of rather expensive transformers, but we feel we are justified in getting the very best transformers and dispensing with the lightning arrester." The next year, 1922, one of the then large users of lightning arresters wrote,[4] "..... the Institute might properly take some steps to protect the smaller companies ..... from the assault of the glib salesman who sells these interesting, sputtering things called arresters, and which actually serve no useful purpose except to the salesman."

However, only 2 years later, 1924, one may find a more rational approach to the problem[5] by Peek. He said, "The extent to which protection should be used is a combined engineering and economic problem. The ... problem ... is to determine the strength of apparatus and the voltage to which it is likely to be subjected." The introduction of the klydonograph and surge recorder at about this time, followed by the cathode ray oscillograph and other lightning measuring devices, and their extensive use in the field and laboratory brought the lightning arrester out from under its cloud of mystery into a clearer atmosphere of cause and effect. In a 1929 paper on klydonograph studies of lightning arresters,[6] one may read, "Much valuable information has been gathered in the last few years on the overvoltages which occur on transmission lines. ...... it has given a reasonable basis for determining the need for lightning arresters, their design, and their proper application."

To summarize briefly the record of the lightning arrester up to the present time, one finds: first, an expressed need on the part of engineers and operators for a protective device for application to lines and equipment subject to the effects of lightning; second, an attempt by manufacturers to meet this recognized need on the part of equipment users; third, a general tendency among designers and users of equipment to discard lightning arresters, altogether, in many instances, with the belief that economics and improvement in service had resulted thereby; fourth, a period in which a great deal of hitherto lacking data were gathered, which not only opened up possibilities for a study of lightning arrester phenomena and lightning protective devices, but also made possible a more rational application of these devices. The last period, however, is comparatively recent, and the lightning arrester today still carries with it some of the disrepute that its early history brought on it.

Present Status of the Lightning Arrester

Present knowledge of lightning phenomena enables engineers to examine the problem of lightning arresters and their application more scientifically. Today, not only the characteristics of lightning, but also the arrester protective characteristics are better understood. Further, the impulse strength of apparatus and equipment is better known, as a result of the great amount of laboratory research and commercial testing that has been carried out over the past few years.

In addition, the effects of ground resistance, arrester lead length, traveling waves, reflections, and steepness of wave fronts have been investigated in great detail, both theoretically and by field research. The phenomenon of displacement of, and rise in, dynamic voltages under fault conditions—another factor affecting arrester performance—is better understood.

All these factors make possible fairly accurate predictions of lightning arrester effectiveness under any particular set of system conditions. Therefore engineers actually can talk of lightning arrester economics and weigh the cost of protection obtained by light-

ning arresters against savings in less damage to equipment and fewer service outages, and do this in many instances on the basis of fairly reliable data.

Broad Economic Considerations

In considering lightning arresters and the problem of their economic application, the authors are fully aware that the problem of lightning arrester economics is only one phase of the general problem of economical protection of apparatus against lightning. There are, for example, at least 2 other means of supplying protection against lightning: first, overinsulation, and second, a protective gap in one of its various forms. These latter 2 means of protection and the arrester itself, in fact, offer various degrees of protection more or less effective under different conditions of application; but none of them offers absolute protection. Sometimes it is more economical to supply only the partial protection offered by overinsulation or gaps, rather than the more highly developed, perhaps partial, protection offered by lightning arresters. In so far as it is possible, therefore, the discussion will be limited to the economics of the lightning arrester itself, showing the general and detailed considerations involved in deciding for or against its use. In doing that, it must be realized, however, that such a decision often is impossible without a full consideration of the alternative methods available under any particular set of conditions.

Table I—Study Made in March 1932 of Lightning Arrester Costs in Per Cent of Transformer Costs (All Installed)

Transformer Rating, Kva	2,300 Volts		6,900 Volts	
	1 Arrester	2 Arresters	1 Arrester	2 Arresters
1.5	36	53	36	60
3	26	38	29	49
5	20	29	24	39
7.5	15	22	19	31
10	13	19	16	27
15	10	14	13	21
25	7	10	9	15
50	4.5	6	6	10

The use of lightning arresters can be justified, in general, only if they are necessary to provide one or more of the following:

1. Protection to life.
2. Protection against fire.
3. Protection of equipment and property.
4. Protection of service.
5. Reduction in cost of equipment.

Economically the protection afforded, whether tangible or intangible, must be equal to or greater than the resultant damage without protection. To evaluate each factor for each particular case encountered is often a difficult, if not impossible task; but often it can be shown that a consideration of only one or more of the foregoing items will justify the use of arresters.

When it is impossible to place a definite monetary value on some of these factors, and a consideration of the others does not point definitely to the economic advantage of arresters, the problem reverts to one of engineering judgment and experience; this has been the basis of arrester application in many cases, perhaps in most cases, in the past, rather than the rigid dollar economy appearing from calculated and estimated savings.

Only within the past few years have any extensive data been available on the relative failure and fuse blowings on distribution transformers with and without lightning protection and with various types of protection. In general, progress in the lightning arrester field in the past few years has been along the lines of determining the impulse strength of apparatus, development of the lightning arrester to withstand service conditions and still supply protection against lightning, and studying and investigating methods of applying arresters in service to accomplish the desired results. Few data are available on electric systems on the cost of damage inflicted by lightning under the 2 conditions: with and without lightning arresters, respectively.

The relative cost of arresters and the relative cost of equipment at different times forcibly enters the problem. The decreasing cost of arresters and variable price of transformers have changed the situation today over what it was 10 or 15 years ago. Fifteen years ago the cost of high voltage arresters was so excessive that very often the overinsulated transformer was a far sounder choice. Today under similar conditions a standard transformer and arrester give a less costly installation and better protection. In a recent case in the authors' own experience, applying a 132 kv arrester on a transformer under ideal conditions saved some 20 per cent in the cost of transformer—an amount sufficient to cover the cost of the arrester installed. Here the arrester clearly was justified by considering only item 3 (protection of equipment and property).

Commenting briefly on the foregoing 5 factors, it is difficult, in general, to assign a monetary value to items 1 and 2, although they sometimes can be evaluated. Item 4 is important but variable, and usually requires an engineering estimate based upon local conditions and experience. Item 5 is a definite figure in many cases, particularly in the high voltage field, that must be evaluated for each particular case. Determination of item 3 requires considerable operating data which have recently been forthcoming in ever-increasing volume so that this problem can be attacked, particularly in the distribution field, on a sound engineering basis. Some analyses of this problem together with supporting data are given in the remainder of this paper.

Arrester Application and Experience

The consideration of arrester application can be divided into 3 separate voltage classes: distribution, medium voltage, and high voltage. The problems of rotary equipment and cables are quite special and fairly complex, and outside the general scope of this paper. The economics of the 3 voltage classes will be considered separately.

Table II—Experience of the Ohio Power Company With Distribution Transformer Lightning Protection

Kinds of Trouble	Transformer Troubles With Various Types of Lightning Protection: No Arrester, Case Ungrounded[1]		No Arrester, Case Grounded[2]		Arrester Direct to Ground, Case Ungrounded[1]		Arrester Direct to Ground and Case[2]		Arrester to Ground and Secondary Neutral[3]		Arrester to Ground, Gap to Secondary Neutral[1]		Arrester to Ground and Case-Gap Neutral[4]		Cost of Trouble, Dollars	
	No.	%*	No.	%*	No.	%*	No.	%*	No.	%*	No.	%*	No.	%*	Total	Unit
1934 Experience																
Fuse blown—no other damage	340	28.2	212	21.4	443	3.45	45	3.20	5	0.61	1	1.41	0	0.00		
Fuse blown—transformer burned out	41	3.4	17	1.72	105	0.82	3	0.21	0	0.00	0	0.00	0	0.00	12,203	73.50
Fuse blown—minor damage	23	1.9	12	1.21	62	0.48	8	0.57	0	0.00	0	0.00	0	0.00	938	8.90
Total cases of trouble	404	33.6	241	24.4	610	4.75	56	3.98	5	0.61	1	1.41	0	0.00		
Average number of installations[5] in service	1,204		990		12,833		1,409		814		72		11			
1935 Experience																
Fuse blown—no other damage	587	37.50	200	18 4	547	4.72	86	5.94	70	2.37	10	6.62	1	3.33		
Fuse blown—transformer burned out	44	2.81	12	1.11	58	0.50	8	0.55	11	0.34	1	0.66	0	0.00	9,835	73.50
Fuse blown—minor damage	33	2.11	11	1.01	48	0.42	6	0.42	9	0.30	0	0.00	0	0.00	1,050	9.5
Total cases of trouble	664	42.3	223	20.5	653	5.64	100	6.92	90	3.04	11	7.29	1	3.33		
Average number of installations[5] in service	1,567		1,085		11,584		1,448		2,956		151		30			
Yearly Average (Based Upon 1934–35 Record)																
Fuse blown—no other damage	414	29.8	206	19.9	495	4.1	66	4.6	38	2.0	5.5	4.9	0.5	2.3	2,050	1.68
Fuse blown—transformer burned out	43	3.1	14.5	1.4	82	0.67	5.5	0.39	5.5	0.29	0.5	0.45	0	0	11,020	73.50
Fuse blown—minor damage	28	2.8	11.5	1.1	55	0.45	7.0	0.49	4.5	0.24	0	0	0	0	994	9.25
Total cases of trouble	483	29.4	232	22.4	632	5.2	78	5.4	48	2.5	6	5.4	0.5	2.3		
Average number of installations[5] in service (total 18,080)	1,385		1,038		12,209		1,429		1,885		112		22			

1. Mostly 2,300 volt transformers on 2,300 and 4,000 volt circuits—urban and rural.
2. Mostly 6,900 volt transformers on 6,900 volt circuits—some 1,200 volt urban and rural.
3. Mostly 2,300 volt transformers on 2,300 and 4,000 volt circuits—urban.
4. Mostly 6,900 volt transformers on 6,900 volt circuits—rural.
5. About 9,690 of installations are single transformers.

* Based upon average number of installations in service.

Distribution System Applications

Some time ago, in attempting to obtain a rational approach to the problem of protecting distribution transformers in the 2,300 and 6,900 volt class a study was made of the cost of lightning arrester protection in per cent of transformer costs. Table I gives the results of this study. The lightning arrester costs include the expense of one ground rod installed. At that time (March 1932) with the meager experience data then available, the companys' best judgment indicated that, taking general experience into consideration, no more than 20 per cent of the total cost could be allowed for lightning arrester protection for distribution transformers. On that basis, protection for 7.5 kva and larger transformers requiring one lightning arrester could be justified in both 2,300 and 6,900 volt classes, but could not be justified if 2 arresters were required. Transformers in the 5 kva size barely could justify the use of arresters, and then only in the 2,300 volt class using one arrester. For the sake of uniformity, however, the practice was set up of installing no protection on transformers of 5 kva and less in either voltage class.

Since that practice was adopted, a field procedure was set up 2 years ago to obtain accurate data on the performance under lightning conditions of distribution transformers in service, to obtain records of not only failures, but also the cost of such failures. These data for 1934 and 1935 on the property of one operating company are given in table II. This record covers distribution transformers on 2,300 volt delta to 12,000 volt star circuits, being largely in the 2,300 and 4,000 volt star class. A summary of the "damage" or trouble record is given in table III. It is shown there that even with standard arrester connection (to ground only) the troubles are from $^1/_4$ to $^1/_6$ of those experienced with no arresters used; and with interconnection (arrester ground connected to secondary neutral either direct or through a gap) the troubles are $^1/_2$ what they are with the standard arrester connection. These relative values hold for all troubles recorded—fuse blowing, burned out transformers, and minor damage (an item that includes arrester failures).

The record of arrester failures is given in table IV, where it is shown that the failures are 0.073 and 0.057 per cent, averaging 0.065 per cent for the 2 years. This indicates a high degree of self-protection for the arrester, perhaps too high over a period of years, a situation that did not exist some years ago.

Referring again to table II, the cost of repairing the damage has been segregated. The average unit costs are as follows:

Renewing blown fuse	$1.68
Repairing or replacing transformer	73.50
Minor damage	9.25

These data, although obtained on only a limited number of transformers and over a period of only 2 years, supply useful information on which to base the value of lightning arresters in reducing property damage.

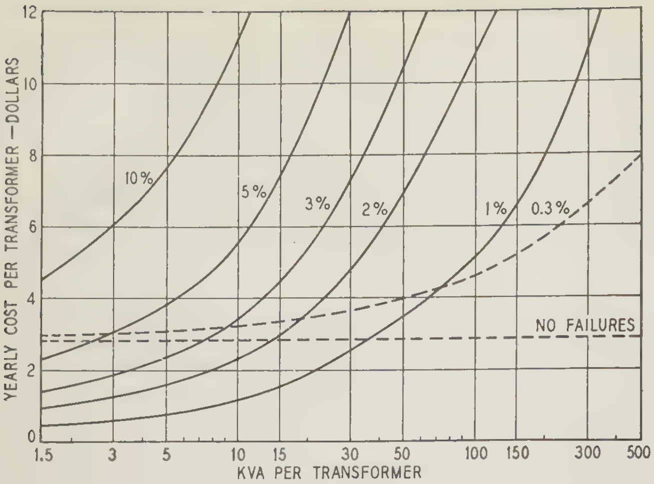

Fig. 1. Cost of maintaining 2,300/4,000–120/480 volt distribution transformers against lightning

Solid line curves are for transformers without arresters; dashed line curves for transformers with one lightning arrester each. Percentages on the curves indicate annual rates of failure based upon the total number of transformers

In attempting an approach to this problem of economics of arrester application to distribution transformers on a broader more general basis than the experience of a single company, a study was made of yearly costs per transformer of maintaining transformers against lightning, both with and without arresters. The results, which are shown graphically in figure 1, are from calculations based upon the following:

1. Transformers at current net prices.
2. One lightning arrester per transformer.
3. One ground rod per lightning arrester except for 6.9 kv transformers which already have one ground rod.
4. Fixed charges, depreciation, maintenance, and replacement of arresters, 20 per cent (includes depreciation and failures at 9 per cent).
5. Credit for damaged transformers, 25 cents per kva.
6. Damaged transformer replaced by new one at present current price.
7. Installation cost of replacing transformer: 5 kva, \$10; 100 kva, \$50; 500 kva, \$100; other sizes, pro rata.
8. Lightning arrester failures, 0.3 per cent.
9. Transformer failures with arresters, 0.3 per cent.

The group of curves in figure 1 show that, under the foregoing assumptions, lightning arresters pay their way on 15 kva and larger transformers in the 2.3–4 kv class if the transformer failures without arresters be approximately 2 per cent; on 10 kva and more, with 3 per cent transformer failures; and on 3 kva and more, with 5 per cent transformer failures. The first part of figure 1 has been redrawn in figure 2 to cover transformer sizes up to and including 15 kva, giving credit to the lightning arrester protection for a 21.6 per cent saving in fuse blowing recorded in the Ohio 1934–35 field experience.

An analysis of the curves in figure 2 shows that on the basis of transformer maintenance alone, lightning arresters are justified on transformers of 10 kva and more for a 2.6 per cent rate of transformer failures without arresters; on transformers of 5 kva and more, for 3.6 per cent rate of failure; and on transformers of 1.5 kva and more, for about 6 per cent rate of failure. It is interesting that the data in figures 1 and 2 were prepared prior to the availability of the data shown in tables II and III, and that the rate of failure for all transformers shown in table III without lightning arrester installations is 2.4 per cent. This is approximately the figure representing the rate of transformer failure justifying lightning arrester installations on transformers of 10 kva and more shown in figure 2.

Table III—Distribution Transformer Lightning Troubles During 1934 and 1935 on the Ohio Power Company System

Trouble	Troubles, in Per Cent of Total Transformers: No Arrester	Arrester With Usual Ground	Arrester With Interconnection
Fuse blown only	25.6	4.1	2.2
Transformer burned out	2.4	0.65	0.3
Minor damage	1.6	0.45	0.22
Total	29.6	5.2	2.7

An analysis for distribution transformers in the 6.6–11 kv class is given in figure 3, based upon the same considerations as figure 1. The results are similar but the capacities of transformers for which arresters are justified are slightly lower than in the 2.3–4 kv range.

It is interesting also to compare the American Gas and Electric Company's 1932 recommendations for lightning arrester protection based upon the study in table I, with those of other operating groups and with the results shown in figure 2:

Company	Capacities of Transformers on Which Arresters Are Recommended or Justifiable
Am. Gas & Elec. Co. 1932 Practice	More than 5 kva
Philadelphia Elec. Co.[7]	More than 15 kva
Edison Elec. Illum. Co. of Boston[8]	7.5 kva and more
Studies embodied in figures 1 and 2	1.5 to 10 kva and more (transformers without arresters failing 2.6 to 6 per cent per year)
Public Service Co. of Northern Ill.[7,8]	Less than 15 kva (lower limit not given)
Am. Gas & Elec. Co. 1935 Recommendation	All distribution transformers

7,8. See references at end of paper.

Although all these studies and recommendations were made entirely independently, the degree of agreement in practice and recommendations is remarkably close. It may be noticed from figure 2 that on the basis of equipment savings alone, arresters on transformers of 1.5 kva cannot be justified except for a rate of failure on an unprotected basis of 6 per cent. The experience cited in table III shows a rate of transformer failure alone on one system of 2.4 per cent. The general experience on several systems[7–9] of the greater frequency of trouble with smaller transformers (generally twice as high for the smaller sizes as for the average), plus the further fact

Table IV—Failures of Distribution Arresters During 1934 and 1935 on the Ohio Power Company System

	1934	1935
Number installed	15,139	15,657
Arrester failures	11	9
Per cent arrester failures, based upon number installed	0.073	0.057
Average per cent arrester failures (1934 and 1935)	0.065	

Lightning arrester failures = 15 per cent of troubles resulting in minor damage, which include arrester failures, cutout damage, and other miscellaneous troubles.

that other cases of damage are reduced considerably when operating with an interconnected arrester, has led within the last 6 months to a decision by the American Gas and Electric Company to install arresters on all transformers regardless of size. An important item in connection with this decision is the extent of the distribution systems and therefore the increasing expense of servicing fuse outages, and also the greater amount of customer inconvenience from individual transformer outages.

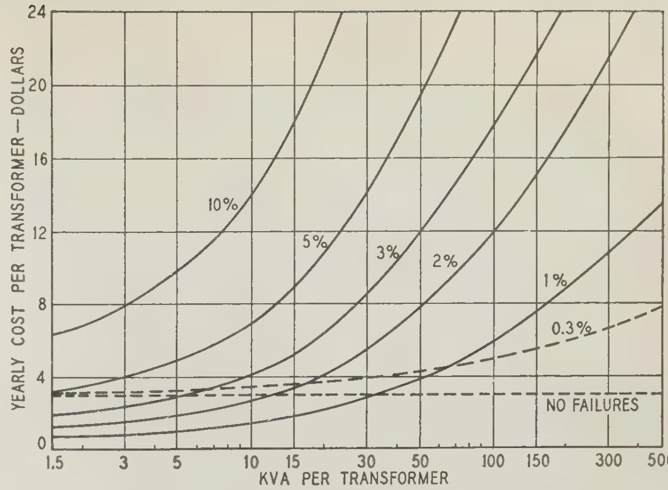

Fig. 3. Cost of maintaining 6,600/11,000–120/480 volt distribution transformers against lightning

Solid line curves are for transformers without arresters; dashed line curves for transformers with one lightning arrester each. Percentages on curves indicate annual rates of failure based upon the total number of transformers

Medium Voltage Applications

In the medium voltage class, arrester application presents some of the problems of both the distribution and high voltage classes. Arresters frequently are used to protect transformers only on a transmission line as is the case with the lower voltage transformers on distribution circuits. They are used also in stations where protection is sought not only for power transformers, but also for other equipment, including instrument transformers, bushings, bus supports, and the like.

Transformers tapped to the line may be considered in the distribution class; on this basis, computation has been made as represented by the curves in figure 4 showing the yearly cost of transformers when protected by arresters and also when not protected. The basic data used are the same as those used for distribution transformers. It is shown clearly that considering maintenance cost only, the normal transformer failure rate must be greater than $3^1/_2$ per cent to justify arresters on transformers with a rating of 15 kva and less. With a transformer failure rate of 3 per cent, arresters are justified only for transformers of 50 kva and more. It appears further from this analysis that except for the larger sized transformers, the use of arresters on medium voltage circuits will be determined by considerations other than the mere cost of maintenance. Thus when it is necessary to take into consideration the fixed charges of the additional spare equipment, it usually will be found that lightning arrester installations in this voltage class can be justified with a failure rate considerably less than 3 per cent.

For transformers in the 66 kv class similar calculations show the same trend, the use of lightning arresters being justified only for progressively larger transformers as compared with those of lower voltage ratings. For example, in the 1,250 kva size a transformer failure rate of 10 per cent, and in the 3,333 kva size a failure rate of 5 per cent is needed to justify lightning arresters on the basis of maintenance considerations alone. With a rate of failure of only 3 per cent, arresters cannot be justified on a maintenance basis alone in sizes up to a 15,000 kva bank. Here again, however, consideration must be given to items other than the mere maintenance costs, and these, in general, as already pointed out, will be of far greater significance and will have to be given the greater weight in any proper decision to use or not to use arresters.

Overinsulation of transformers, as was stated hereinbefore, is one method of protection, partial though

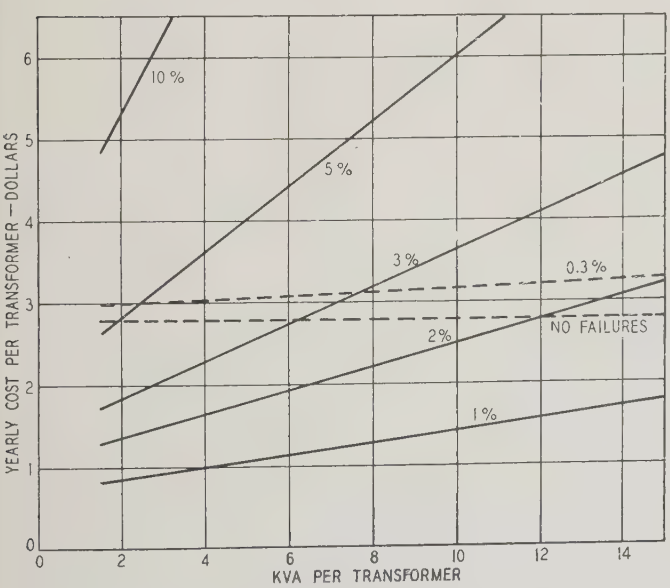

Fig. 2. Cost of maintaining 2,300/4,000–120/480 volt distribution transformers against lightning

Solid line curves are for transformers without arresters on basis of 21.6 per cent blown fuses; dashed line curves for transformers with one lightning arrester each. Percentages on curves indicate annual rates of failure based upon total number of transformers

Table V—Relative Costs of Lightning Protection for 500-Kva 66-Kv Transformers

	1925	1935
Transformer, 139 kv test	100	100*
Transformer, 185 kv test		149
Transformer, 198 kv test	153	160
Lightning arrester installed	76.5	41

* 1935 costs about 13 per cent higher than in 1925, but used as 100 for 1935 comparison.

it may be; and it was stated also that the relative cost of transformers and arresters at different times enter into the problem of determining the economic limits between which arresters can be applied. In this connection, the experience of the American Gas and Electric Company with 66 kv power transformers may be of interest. About 1918, engineers of the company were faced with the necessity of making a choice between the then standard insulated transformers with lightning arresters (generally aluminum cell type) and overinsulated transformers without arresters. Table V gives a summary of this situation, which continued substantially unchanged from 1918 to 1925 (although by that time newer arresters such as the oxide film and autovalve types had been developed), and also of the situation in 1935. The high cost of lightning arresters in 1925 added 76.5 per cent to the cost of the transformers when they were used. The addition of 50 per cent to the transformer insulation (198 kv test instead of the standard 139 kv test) increased the cost of the transformer only 53 per cent. While, of course, it cannot be stated today that a triple test transformer is the equivalent of one protected with a modern lightning arrester, the general knowledge available in 1925 indicated that satisfactory service might be expected with the triple insulated transformer. The installation therefore was made on the basis of overinsulation, and it is gratifying to find that after some 10 years of service the absence of transformer failures has justified the decision made.

In the second part of table V, the comparison of overinsulated transformers on today's basis against a standard transformer with a modern lightning arrester gives an entirely different picture. Assuming a transformer today with a cost of 100 per cent, overinsulation increases the cost of the transformer 60 per cent while the use of a standard lightning arrester installed adds only 41 per cent. Therefore, it is cheaper at the present time, in this particular size and voltage class, to install a standard insulated transformer with a lightning arrester than to use an overinsulated transformer with its less certain protection against lightning surges. Thus the change in cost of transformers and lightning arresters, and particularly the reduction in the cost of lightning arresters, warrants their use today in this case where they could not be justified some 10 years ago.

Analysis made so far has dealt largely with the use of the single lightning arrester to protect one transformer, and the yearly maintenance costs presented have been set up on that basis. When lightning arresters are applied in substations, however, even though the arrester be installed close to the transformer, it reasonably may be assumed that the protective influence of the arrester extends farther than the terminals of the power transformer—in fact, to such equipment as bushings on circuit breakers, current and potential metering devices, reactors, and similar equipment. Just how far this protection extends will depend on the strength of the insulation to be protected, the arrester voltage characteristics, ground resistance, and distance between the arrester and such apparatus. Taking these factors into consideration, there may be many cases where a lightning arrester, considered for installation on a single transformer bank forming part of a substation that has several high voltage lines, cannot be justified from a consideration of the protection given to the single transformer bank, but can be amply justified when considering the protection, even though partial, afforded by the arresters to the equipment associated with the various lines.

High Voltage Applications

The problem of applying arresters in the high voltage field assumes greater importance, and probably has been given more careful consideration than in lower voltage ranges. The cost of equipment involved, the loss of service, and possibility of long interruptions and of attendant damage is high; but here again, until recent years, arrester application has not been on a particularly sound basis. To add to the difficulty, reliable statistical data have been almost nil. Unfortunately, the data on the performance of equipment of this voltage class are still meager and scattered, perhaps because those who have had trouble without arresters have been reluctant to air their troubles, and because those who did use arresters and had few failures have apparently had little to report.

On the 132 kv interconnected system of the American Gas and Electric Company, arresters always have been installed at all important stations, only 13 per cent of the transformers numerically and 0.8 per cent in kva capacity not being protected by arresters.

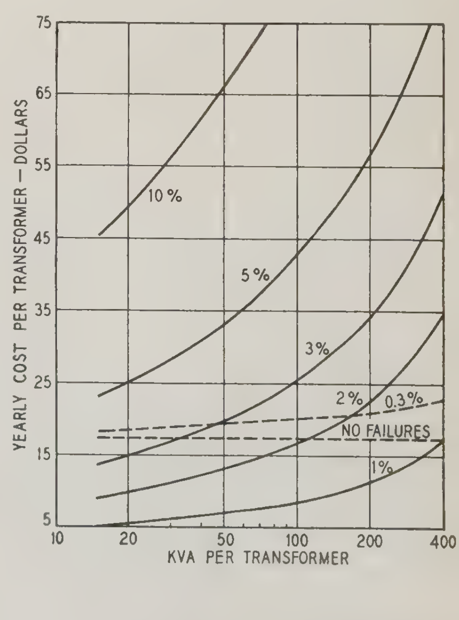

Fig. 4. Cost of maintaining 33—2.4/4.1 kv transformers against lightning

Solid line curves are for transformers without arresters; dashed line curves for transformers with one lightning arrester each. Percentages on curves indicate annual rates of failure based upon the total number of transformers

The complete record of the transformers under lightning conditions since the first transformers were installed in 1918 is given in table VI. This group of transformers, totaling 1,380,154 kva, comprises 159 (equivalent single phase) transformers, and covers a service record of 1,530 transformer years. Of the transformers having lightning protection, the failure record from lightning has averaged 0.39 per cent per year. This rate of failure is one obviously not to be regarded with equanimity. It indicates, for example, from 47 bank installations an expected average failure of one every 2 years. That the failures have been as high as they were in spite of the use of lightning arresters, is ascribable to several causes previously pointed out,[10] as well as to the lack of co-ordination generally between the arrester design and the design of the transformer it was intended to protect.

One solution of this is undoubtedly the overinsulated transformer. Of the failures on transformers recorded in table VI, none occurred on overinsulated transformers whether lightning arresters were installed or not. The present objection to overinsulation in large installations, however, is the cost; and although the use of overinsulation has been justified in the past, it would appear that at the present time, with a better knowledge of co-ordination available, properly applied lightning arresters can give an over-all cost of equipment that is less than can be obtained by overinsulation, and better protection also should result.

A clearer insight into some of the underlying reasons for the performance data shown in table VI can be obtained from the analysis shown in table VII. Here have been assembled the best available data on protective characteristics of the arresters and the insulation strengths of transformers in the 132, 66, and 33 kv classes in general use on the American Gas and Electric system. Some of the early arresters and many of the later ones in service were of types *A* and *B*, and it is believed that an examination of table VII will disclose the reason why some transformer failures with arresters installed did occur. However, as the knowledge of lightning phenomena and of arrester performance improved, and with the operating experience obtained with types *A* and *B* arresters as a background, arresters gradually were changed to type *C*, and in 1933 practically all the old type of arresters were altered to type *D*. Since then there have been no transformer failures on the 132 kv system, although 3 arrester failures have occurred. Thus, the failures have been transferred definitely from the equipment to be protected to the protecting equipment, which is a change in the right direction. However, it is believed that in the long run further study of the problem will make possible a reduction, if not elimination, of arrester failures. It is possible that the reduction in the number of active elements in the arrester has resulted in a situation where the safe cutoff value of dynamic voltage on the arrester is very close to its limit, but so far the plan apparently has proved effective in supplying protection to the transformers, and this is in accordance with what would be expected from close co-ordination of lightning characteristics. Considering that with each year of additional service of the transformer there is reason to believe that the transformer loses some of its strength, the experience with such operation obtained so far, although not conclusive, definitely seems to indicate that it is possible to obtain 100 per cent operation with a properly applied arrester of modern design or one that has been brought up to date.

It is interesting to study the comparative maintenance costs of high voltage transformers with and without arresters on the same basis as was followed for distribution and medium voltage transformers; this has been done in figure 5 for 132 kv transformers using the same basic set-ups as for figures 1, 3, and 4, with the following exceptions:

1. Standard type lightning arrester fixed charges assumed at 15 per cent (instead of 20 per cent).
2. Cost of repairing damage, 20 per cent of initial transformer cost (instead of complete replacement of transformer).

It may be seen from figure 5 that lightning arresters supplying protection to one transformer only cannot be justified on a maintenance basis on transformers of any size where the normal transformer failure rate is less than 3 per cent. Where the failure rate is 5 per cent, they are justified only for transformers having capacities greater than 8,000 kva, and where the failure rate is 10 per cent, only for transformers of more than 2,500 kva. Both these rates of failure, i. e., 5 and 10 per cent, are normally far in excess of anything generally likely to be encountered in service. Here again there is usually so much additional equipment in a normal 132 kv sta-

Table VI—Lightning Experience of American Gas and Electric Company on 132 Kv Power Transformers (Single Phase Basis)

Total transformer capacity connected—kva	1,380,154
Number of transformers (single phase equivalent)	159
Transformers protected with lightning arresters	141
Transformers without lightning arresters	18
Transformer years of service with lightning arresters	1,299
Transformer years of service without lightning arresters	231
Transformer failures with lightning arresters	5
Per cent transformer failures per year with lightning arresters	0.39

Table VII—Protective Characteristics of Lightning Arresters, as Used With Transformers on American Gas and Electric Company System

	Impulse Voltage Characteristics (Kv)					
Circuit Voltage	132 Kv		66 Kv		33 Kv	
Type of Arrester	Short Time	Long Time	Short Time	Long Time	Short Time	Long Time
A	1,050	584	525	292	262	146
B	918	510	459	254	230	127
C	720	400	360	200	180	100
D	635	352	317	176	159	88
E (modern 100%[1])	540	565	275	285	145	150
F (modern reduced[1])	430	450	220	230	112	115
Safe dielectric strength of transformer insulation[2]: Max	720		480		210	
Min	455		235		210	
Avg	575		400		210	

1. Catalog data.
2. Based upon manufacturer's estimate of strength of transformers in actual service on the system.

tion that the total maintenance cost of the arrester must be apportioned to all equipment it protects, to reach a proper basis of protection costs, and this must be worked out carefully for each individual case. However, in the great majority of the 132 kv stations on the American Gas and Electric system, the importance of continuous service is such a large item in a total evaluation of the annual cost of the station that arresters have been used in approximately 90 per cent of the installations. In the remaining 10 per cent, overinsulation has been employed either as part of the original design or as part of the rebuilt job, subsequent to failure.

Reduced Insulation Transformers With Lightning Arresters. Experience with overinsulation with or without lightning arresters, and particularly the experience with lightning arresters as progressive co-ordination was brought about between the protective level expected to be maintained by the lightning arrester and the insulation strength of the transformer to be protected as shown in table VII, brought this out forcefully: If a lightning arrester can be relied upon to maintain voltage levels on a transmission system of the order shown by type *F* in table VII, then transformer insulation levels considerably below those being employed as standard at the present can be used entirely successfully and yet give a grade of reliability considerably superior to what was possible with standard transformers and standard arresters, say, of the 1925 type. It is obvious that the savings this would make possible would increase progressively as the voltage increased and as the size of transformer is increased.

This is clearly shown too in figure 5 where the savings possible with the reduced insulation transformer have been plotted for 132 kv transformers of various sizes. The curve shown as a heavy line is based upon 20 per cent saving in initial transformer cost by using reduced insulation levels, balancing the fixed charge of the arrester plus 0.3 per cent failures of arresters and transformers (assumed) against the fixed charges on the 20 per cent additional price for transformers not equipped with arresters. Fixed charges on this item have been taken as 12 per cent, and the curve shows the calculated yearly saving by using one arrester per transformer on the foregoing basis. Thus it appears that even though it be assumed that 0.3 per cent transformer and arrester failures occur on a properly co-ordinated lightning arrester transformer installation, and considering the arrester to provide benefit to no piece of equipment in the station other than the transformer, there still results a net saving for transformers of all sizes greater than 2,500 kva, and this item becomes quite appreciable in transformers of the larger sizes. Thus, for example, in the 16,333 kva size the saving amounts to $600 per transformer per year, *compared with a standard transformer without any protection at all,* and assuming no greater rate of failure for this unprotected transformer than for the protected transformer with reduced insulation.

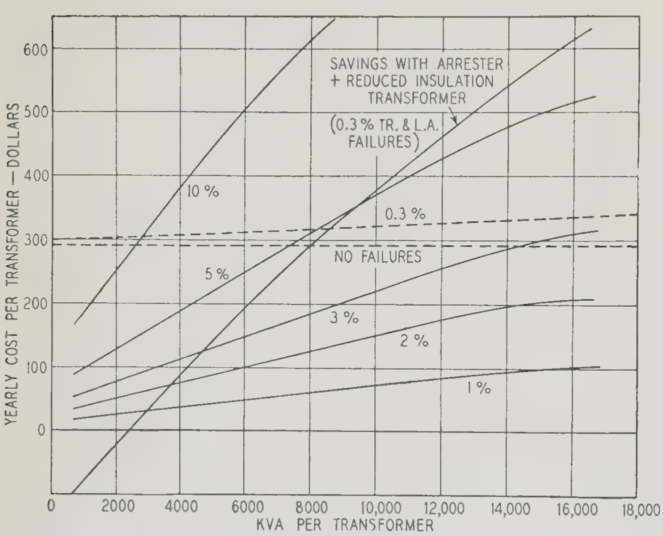

Fig. 5. Cost of maintaining 132 kv transformers against lightning

Solid line curves are for transformers without arresters (except one which is labeled otherwise); dashed line curves for transformers with one arrester each. Percentages on curves indicate annual rates of failure based upon total number of transformers

Considerable transformer and lightning arrester application along these lines actually has been carried out on the system with which the authors are associated, and this, it is believed, is an outstanding result of the work carried out in the last 10 years on insulation and lightning arrester co-ordination. Typical cases where this has been done are given in the following paragraphs.

Recent Examples of Arrester and Transformer Insulation Co-ordination. One of the first transformer installations made by the American Gas and Electric Company to take advantage of the more definite knowledge of the protective characteristics of the arrester and insulation strength of the transformer is that of a 138-kv 30,000-kva bank of transformers installed in 1934. Two means were employed to reduce the cost of this installation to a minimum: First, the transformer was built with reduced insulation, receiving an induced test of 219 kv against the standard test of 277 kv. Second, the lightning arrester design was studied with the purpose of reducing its rating within practical limits and thereby lowering its terminal voltage under lightning conditions. In addition, the lightning arrester was located to supply maximum protection by mounting the arrester directly on the transformer tank. The transformer with lightning arresters (both 132 kv and 33 kv arresters) mounted on the tank is shown in figure 6. By adopting this plan, the savings in the first cost amounted to approximately 22 per cent over the cost of a standard insulated transformer. In addition, the cost of the lightning arrester and its installation also was reduced. This transformer has been in service through 2 lightning seasons and so far has given perfect operation.

The second installation is that of a 3-phase 138-kv 5,000-kva transformer where the transformer insulation was cut to a 231 kv test as compared with the standard of 277 kv. The lightning arresters were mounted as close as possible to the transformer tank, but not on it. The savings in transformer cost

amounted to slightly more than 20 per cent, and this transformer also has given satisfactory service through one lightning season. Neither the transformer nor the arrester ratings were cut to the extreme limit in this case, although a reduction in the standard practice for each was made.

The third case refers to a 1,500-kva 3-phase 138-kv transformer designed for standard test voltage and using a lightning arrester mounted on the transformer case. The arrester was of reduced rating. This selection was made in preference to an overinsulated transformer. The saving in first cost of the transformer here again was more than 20 per cent by taking advantage of lightning arrester application and obtaining the maximum protective value of a reduced rating arrester.

As a fourth instance, the company is putting into service at the present time a 40,000-kva 138-kv bank of transformers with reduced insulation having an induced test of 219 kv compared with the standard of 277 kv. Here also the lightning arrester is of reduced rating and will be mounted directly on the transformer case.

The fact that satisfactory service has been rendered through 2 lightning seasons by the transformer where both the insulation and lightning arrester ratings were cut to the limit indicates not only the practicability of the scheme, but also that substantial savings can be effected by properly applying present knowledge of impulse strengths of insulation and protective value of arresters. The authors believe what has been reported here is only a beginning in the type of work that will be done in the next few years along the lines of applying lightning protection to transformers at a reduced over-all cost.

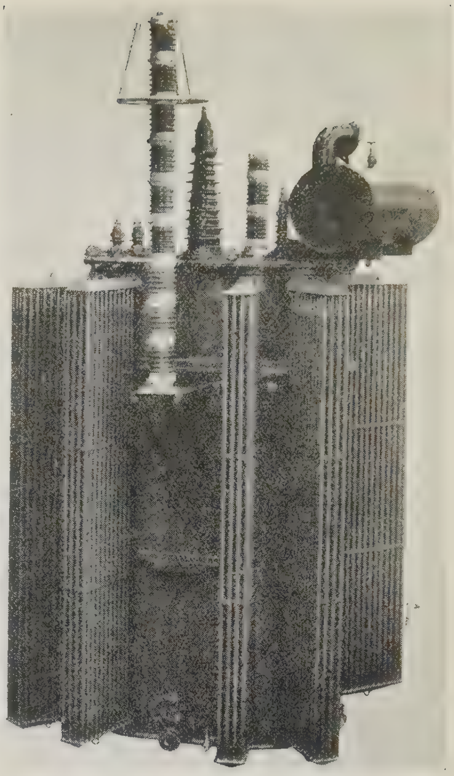

Fig. 6. A 132–33 kv transformer with co-ordinated lightning arresters mounted on transformer tank

Summary and Conclusions

1. The early disrepute of the lightning arrester was attributable largely to lack of fundamental data on the protective characteristics of the arrester, of safe insulation strength of the apparatus to be protected, of knowledge of lightning phenomena, and of mechanical defects of the arrester itself.

2. The intensive study and research on the problem of protecting apparatus against lightning, carried out largely within the last 10 years, have yielded a knowledge of lightning phenomena which gives promise of producing an arrester that, although not perfect, will be substantially effective in supplying protection without being a hazard to operation.

3. In the distribution field, the arrester in general clearly pays its way on a maintenance basis only in protecting transformers in capacities of 15 kva and more. For transformers of all capacities it pays its way where the normal rate of transformer failures is high, and it usually can be justified, except under unusual conditions, for all capacities if consideration be given to factors other than maintenance cost.

4. In the medium voltage field the arrester is not so easy to justify as in the distribution field, and considerations other than maintenance cost usually must be taken into account to determine the advisability of its use.

5. Where high grade protection is required in the medium voltage field, it is usually cheaper in first cost at the present time to use standard insulation and a lightning arrester than to use an overinsulated transformer without arrester, with the degree of protection to be expected greatly in favor of the arrester. The same applies to the high voltage field with a distinct annual saving indicated for the arrester equipped transformer in transformers of 2,500 kva and more.

6. In applying arresters to high voltage equipment, it is most economical to eliminate the arrester from the line entrance and install it close to or on the equipment that is in most need of protection.

7. By co-ordinating the lightning arrester and transformer insulation, first cost savings in the order of 20 per cent or more have been made on recent high voltage transformer installations of both large and small ratings.

8. By derating the arrester in the higher voltage classes on solidly and effectively grounded neutral systems, further savings in first cost and maintenance are possible.

9. Lightning arresters on high voltage transformers usually can be justified (as compared with standard transformers without arresters) on the maintenance basis alone, without considering the protection afforded other equipment in a station, although this feature as well as other considerations such as protection to service and the like are equally or more important and must be considered in determining the over-all economy of the arrester.

10. The broad lightning arrester problem, including lightning arrester economics, is related closely to the other broad problem of station protection, which is beyond the scope of the present paper.

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Sliding Contacts—

Electrical Characteristics

Experiments with oxidized and oxide-free materials indicate that the electrical characteristics of the ordinary sliding contact, such as that between a carbon or graphite brush and a copper slip ring, are dependent upon the oxide film on the surface of the ring. Results of these experiments are presented in this paper, together with an explanation of the breakdown of this oxide film by the increase of current through the contact, based upon these results. Tests to determine the effects of liquid films on the contact voltage drop, and the variation of thermal voltage in a sliding contact also are reported.

By
R. M. BAKER
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

THIS paper is intended to expand and furnish further experimental evidence to substantiate the view on sliding contacts exposed by the writer in 2 short articles published recently,[1,2] and like these earlier articles will deal principally with the effect of oxide films on the electrical characteristics of sliding contacts. The simple experiments described are so far from being a thorough investigation of the electrical behavior of sliding contacts that the writer hesitates to publish them. However, they illustrate the effect of oxide films very nicely, and are unusual enough that they perhaps may attract the interest of others working in the field and thus lead to some really thorough investigations. The principal findings and conclusions reached are briefly:

1. It is shown that the oxide film on the ring surface accounts for the electrical characteristics of ordinary sliding contacts. This film is broken down by the passage of current, and the contact resistance, therefore, decreases with increasing current. The process of breakdown is probably through the building of metallic bridges out through the oxide.

2. Liquid films can affect contact drop directly only when these films are of oil or some other liquid having a low vapor pressure. Water films probably produce a very desirable lubricating effect in a sliding contact, but do not tend to raise the brush off the ring and, thereby, increase the contact drop. The water films which lubricate the contact are thin in comparison with the unevenness in the contact and are extremely tough. The current flows through these very thin films with no appreciable loss in voltage.

3. Appreciable thermal voltages can be measured in a sliding contact if the ring carries an oxide film. These voltages disappear immediately when the oxide film is removed by sanding the ring surface.

A paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 28–31, 1936. Manuscript submitted Oct. 24, 1935; released for publication Nov. 25, 1935.

1. For all numbered references, see list at end of paper.

Breakdown of the Oxide Film

Since one of the most outstanding characteristics of sliding contacts is the change in contact resistance with current, this will be used to test the idea that the contact resistance of the sliding contact between a brush and a rotating slip ring is governed by the existence of an oxide film on the surface of the ring and the process by which this film is broken down or repaired as the current through the contact changes. For the sake of definiteness the contact will be assumed as that between a carbon or graphite brush one square inch in area, operating with a pressure of 2.5 pounds on a copper slip ring. The behavior of such a contact depends somewhat on polarity, but this refinement may be omitted in the preliminary discussion.

If the contact is carrying a current of 50 amperes, its resistance will be about 0.02 ohm. This is the condition under which the contact normally would operate in service. Assume now that the current through the contact suddenly is reduced to 2 milliamperes. The voltage drop in the contact at first will be very low; but if one calculates the resistance of the contact from the readings of contact drop and current through the contact just after the current has been reduced, the resistance will be found to have risen to a value 3 or 4 times as high as it was with 50 amperes flowing. This is a very small increase in comparison with what may be observed if the contact continues to operate at the low current. After an hour or so it will be found that the contact drop has risen to perhaps 0.3 volt and the contact has a calculated resistance of 150 ohms, or 7,500 times the resistance observed at a current of 50 amperes. The building up of this high resistance in the contact is associated with the formation of an almost continuous semi-insulating layer of oxide on the surface of the ring. The formation of this film is greatly accelerated by the polishing action of the brush, for the brush plasticly deforms the small irregularities on the ring surface and thus hastens oxidation.[3] A good demonstration of this effect can be had by scratching a line with a sharp instrument across the surface of a piece of copper, and allowing the piece to be exposed to the air for several days. A bright red band will form along the sides of the scratch demonstrating the increased thickness of oxide in that region. The small rapid increase in contact resistance when the current is first reduced will be explained later.

If, after the contact has been carrying the low current for some time and the contact resistance has reached a value of 150 ohms, the current suddenly is increased to 50 amperes, one might expect the appearance of a very high voltage in the contact. If there were no change in contact resistance at the instant when the current is increased, the contact

drop would be 7,500 volts, which is of course absurd. As a matter of fact, an oscillogram of the contact drop taken under these conditions shows the contact drop at the instant of throwing the 50 amperes through the contact to be only slightly greater than it is after steady state conditions are reached. It might be argued that the magnetic oscillograph is too slow to record the phenomenon; but it must be remembered that if the cause of the high contact resistance at the low current is ascribable to the oxide film on the ring surface (later this will be shown to be true), the breakdown process must continue in the contact for one complete revolution of the ring, and such a slow phenomenon can be recorded very easily by the magnetic oscillograph. It is necessary, therefore, to find a low voltage breakdown process to explain the change in resistance in the contact when the current suddenly is increased from 2 milliamperes to normal current (50 amperes). A seemingly plausible explanation follows.

When the contact is carrying the low current, the oxide film on the ring is practically continuous and serves to insulate the brush rather effectively from the ring. When the current suddenly is increased, voltage will appear across some spots in the oxide film of sufficient magnitude to break down this film in much the same manner as any thin layer of poor insulation is broken down. The breakdown is associated with considerable heat, and metallic bridges will be formed through the oxide film.[4] If the original bridges are not large enough to carry the current without melting, they will grow, possibly by reducing the oxide in their neighborhood, until bridges of sufficient cross section exist to carry the current of the contact. As the melting voltage for copper is only 0.45 volt,[4] this process need not require a high breakdown voltage. It is necessary only to get the bridges started (breakdown of perfect films may require 100 volts or more), and weak spots in the film, especially with the help of the abrasive action of the brush, will take care of this.

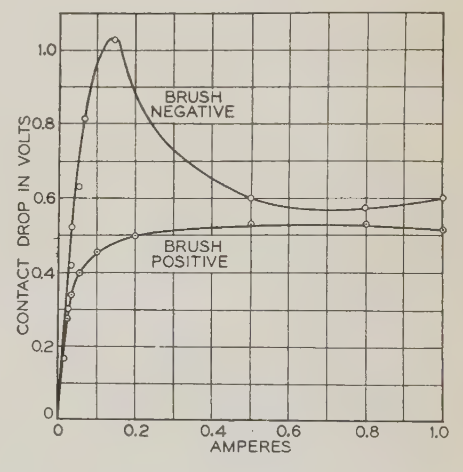
The picture of a sliding contact thus becomes rather complicated. The brush and ring make mechanical contact over only a fraction of a per cent of the polished brush face because of the inherent lack of smoothness in the contacting surfaces; and even at these points of mechanical contact, the brush and ring are separated by a semi-insulating oxide film, which in turn is broken down more or less completely depending upon the amount of current through the contact. If the film could be broken down completely at the points of mechanical contact, the contact resistance would be practically the same as if the brush were operating on a gold ring (oxide-free ring). This condition is approached at unusually high current densities. The other extreme of course is obtained when the points of mechanical contact between the brush and the ring are separated by a practically continuous (not broken down) oxide film. When the film separating the brush from the ring at points of mechanical contact is broken down by fine bridges, the current of the contact must spread out from the ends of these fine bridges into the material of the brush, and this gives rise to a spreading resistance in the brush. An increase of current through the contact increases the size of the bridges and thereby decreases the spreading resistance in the brush as well as the resistance of the bridges themselves. Thus it is seen that the spreading resistance of an oxide containing contact decreases with an increase of current, whereas in an oxide-free contact (graphite brush on gold ring) the spreading resistance, for a large range of currents, is independent of current.

It was mentioned earlier that a sudden but small recovery in contact resistance appeared just after the current in the contact was reduced from normal value (50 amperes) to the low value (2 milliamperes). This change is very probably caused by the rapid oxidation of the ends of the bridges exposed to the air when the breaking down effect of the heavy current is removed. The slow but large change in the contact resistance occurs only when the oxidation has penetrated well below the surface of the original oxide film, and the bridges are practically destroyed by being converted again into oxide.

In an attempt to obtain some clue as to the method by which a film breaks down as the current through the contact is increased, the electrical characteristic of a sliding contact was studied very carefully in the low current region. In the test, a soft graphite brush operated on a small copper ring (3 inches in diameter) running at a speed of 1,200 rpm. To make a test the current was set at a very low value (10 milliamperes) and the ring was allowed to polish for hours until the contact resistance was about 100 ohms. The current then was increased in small steps, allowing an equilibrium condition to be established after each change. Typical curves obtained are shown in figure 1. The test was repeated

Fig. 1. Breakdown of thin oxide film on copper slip ring by gradual increase of current

Ring 3 inches in diameter running at a speed of 1,200 rpm; brush contact area 0.4 square inch



on an oxide film which instead of being produced by polishing of the brush was produced on the clean ring surface by heating the ring several minutes at a temperature of 150 degrees centigrade in air. The breakdown of this film gave curves very similar to those shown in figure 1. The experiment was repeated several times; and in every test for the polarity where the current flowed from the ring to the brush (brush negative), the curve was found to rise to a maximum and then decrease before rising

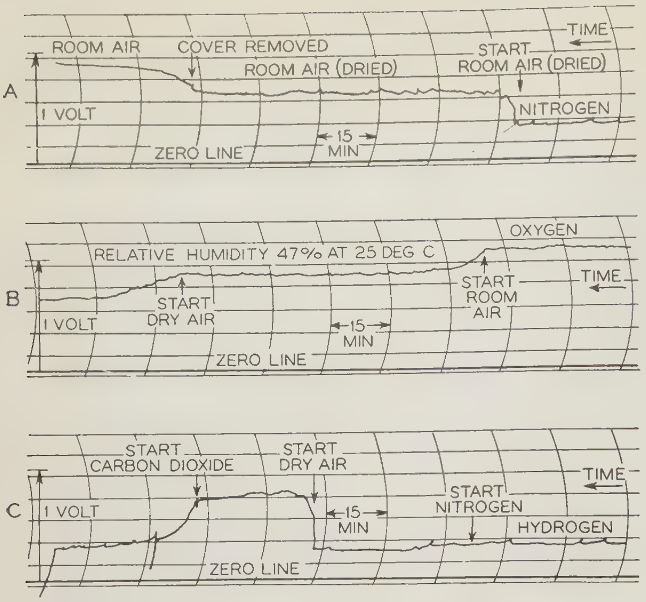


Fig. 2. Records of contact voltage drop in different gases; carbon brush on copper ring

Diameter of ring 1.75 inches; ring speed 1,000 rpm; brush contact area 0.125 square inch; current 5 amperes

again with a further increase in current. The opposite polarity showed no such tendency.

No attempt will be made to give an accurate explanation of the difference in the characteristics for the 2 polarities, as the present knowledge of the processes of breakdown in oxide films is insufficient. It can only be hoped that the understanding of such observations will improve as more data are accumulated.

Contact Drop in Various Atmospheres

To make a simple investigation of the effect of different gases on contact voltage drop, a small slip ring set was built and enclosed under a bell jar so that the space around the contacts could be filled with different gases, or could be pumped down to an air pressure of about 0.2 millimeter of mercury. The rings had a diameter of 1.75 inches and were run at a speed of 1,000 rpm. The brush on each ring consisted of a flat piece of slightly abrasive electrographitic brush material fitted with the necessary shunts and held in position by a box and pressure finger in such a way as to produce very good mechanical conditions in the contact. The single brush on each ring had a contact area of 0.125 square inch and was operated, unless otherwise specified, at a current of 5 amperes, or a current density of 40 amperes per square inch.

The results of one series of tests made with this equipment are shown best by the curves of figure 2. These curves are for a copper slip ring and were taken with the polarity such that the current flowed from the brush to the ring (brush positive). This polarity was chosen purposely to eliminate the question of possible "copper picking," which very often is observed with the opposite polarity.

Starting at the right-hand side of curve A, the contact had been operating in nitrogen with a low contact drop. When dried room air was admitted through a drying tube, the contact drop increased in a few minutes to double its previous value. The removal of the bell jar cover and the introduction of moist room air resulted in further increase as shown.

In curves B and C, one may see how the contact drop varied as the atmosphere around the contact was changed successively from pure oxygen to room air, to dry air, to hydrogen, to nitrogen again, to dry air, and finally to carbon dioxide.

It is interesting to observe that for all the oxygen free atmospheres, the contact drop had about the same low value. The contact drop in nitrogen was slightly lower than in hydrogen, probably because of the somewhat greater oxygen impurity in the commercial hydrogen used.

Since the presence or absence of moisture in air made appreciable difference in the contact drop, an experiment was made in which a nitrogen atmosphere with varying amounts of moisture was used. The same low value of contact drop was observed in nitrogen, independent of moisture content, even when the moisture content corresponded to saturation at a temperature of 25 degrees centigrade. Thus, it is concluded that the absence or presence of oxygen in the atmosphere makes a large difference in the contact drop, whereas the presence or absence of moisture in a nonoxidizing atmosphere does not increase the contact drop appreciably.

In figure 3 are shown curves of contact drop versus current when the contact was operating in nitrogen. It is important to notice that these curves are much straighter than the familiar curves obtained in air at atmospheric pressure. The oxide film had been so far removed by the combined action of the reduced rate of oxidation and the abrasive action of the brush, that it no longer permitted the large change of contact resistance with current. As may be seen from these curves, the contact resistance at very low currents was hardly twice what it was at the highest current. In air the ratio would be several thousand to one.

Liquid Films in the Contact

The foregoing evidence is certainly against any theory that tries to explain the electrical characteristic of a sliding contact on the assumption that the brush is supported and separated from the ring almost completely by a liquid film. For an extremely interesting and clever presentation of such a theory, the reader is referred to an article published[5] in 1927.

The observation that a contact does not need a liquid film to explain variations in resistance does not mean that liquid films cannot produce an increase in contact resistance. This would be absurd, for it is well known that a small amount of oil placed on a ring will tend to raise the brush off the ring and increase the contact drop. Even blowing one's breath on a small slip ring will often condense enough moisture on the surface of the ring to lift the brush and increase the contact drop; but when the film is of water, it soon evaporates until it is very thin in

comparison with the unevenness in the contact surfaces and no longer can be effective in increasing the contact resistance.

It is obvious that even when a liquid film has become too thin to be effective in raising the brush, it still must separate the brush effectively from the ring at the points of mechanical contact, and all the current flowing through the contact points must flow across the very thin liquid film. This can occur, however, with practically no voltage drop, as the resistance of these thin films is extremely low.[6]

The tenacity of the thin adsorbed films on the surfaces of solids is illustrated forcibly by the difficulty of removing gas from vacuum tube parts after the tube is assembled. Even with the best vacuum obtainable, the adsorbed gas is removed only after heating the parts up to a temperature of 600 degrees centigrade or more. Because of their tenacity, these liquid films, while not affecting the electrical characteristic of the contact directly, probably cover over and lubricate the points where the solid material of the ring and brush come together, even though the unit mechanical pressure at these points is very high. An interesting description of this effect in vacuum switches is given in a previous article.[6] When a vacuum switch has been treated out so that the small copper contacts are clean, they tend to stick together so that upon opening a distinct click is heard. This effect disappears almost immediately when a small amount of water vapor is admitted, even though the corresponding change in contact resistance is practically negligible.

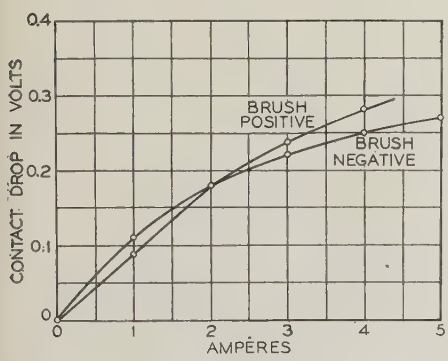


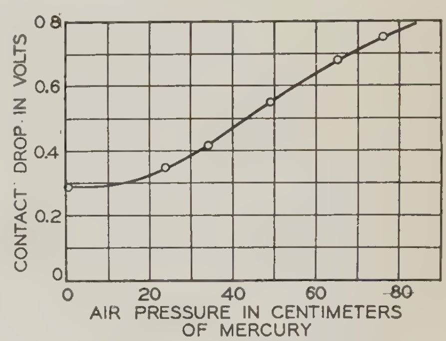
Fig. 3. Contact voltage drop versus current for electrographitic brush on copper ring running in nitrogen

Diameter of ring 1.75 inches; ring speed 1,200 rpm; brush contact area 0.125 square inch

An evidence of the lubricating effect of thin films in sliding contacts is shown by the fact that in general, and especially with some grades of brushes, a low humidity in the atmosphere around the brushes results in increased friction and lowered contact drop. This effect would be expected if the lower moisture content should reduce the lubrication of the contact to the point where the brush begins to grab onto and abrade the surface of the ring. The tendency toward abrasion with metal graphite brushes would be even greater than with straight graphite brushes, and this probably accounts for the phenomenally rapid brush wear observed on some synchronous converters operating in a low humidity atmosphere.

Since slip rings operate generally at a temperature lower than, or in any event not much higher than the boiling point of water, it is to be expected that water vapor would be adsorbed to build up a film of greater thickness than other gases such as nitrogen or carbon dioxide, which boil at a very much lower temperature. It does not seem likely, however, that a change in atmospheric moisture of from 1 grain per cubic foot to 6 would change appreciably the thickness of the adsorbed film on the surface of a piece of metal exposed to the atmosphere, and yet the abrasion of brushes on machines seems to vary greatly with this same change in atmospheric moisture. Possibly this can be explained if one remembers that the surface of a slip ring is passing continually under the brushes, and is being required to carry current. This means that the heating effect of the current as well as the heating and scrubbing effect of the friction is tending continuously to remove the adsorbed film from the surface of the ring. If the film were not being repaired continually by the supply of moisture in the atmosphere, the adsorbed film very soon would disappear. If, however, the striking of water molecules on the ring surface can repair the film as fast as it is destroyed, the operation of the contact will continue to be satisfactory. Thus, it is to be expected that there will be no definite lower level of moisture content in the air that will insure satisfactory operation, but that this minimum will depend upon the nature of brush and ring material (need for lubrication), speed of rotation, number of brushes per track, ring temperature, and other factors. In short, the minimum safe moisture content will depend upon the balance between the ease of repairing the film and the tendency for the film to be removed.

Fig. 4. Effect of reduced air pressure on contact voltage drop



Contact Drop at Low Air Pressures

With the small slip ring set described hereinbefore, it was undertaken to determine the effect of reduced air pressure on contact drop. A typical curve obtained is shown in figure 4. As the pressure was reduced, the contact drop decreased to about 0.3 volt at an air pressure of about 20 centimeters of mercury and did not seem to be affected much by a further reduction in air pressure, even though the pressure was reduced to 0.2 millimeter and was maintained at this low value overnight. As a matter of fact, when the experiment first was tried, the contact drop decreased to a minimum value and with further decrease in pressure began to rise again. This later was found to be attributable to the oil vapor given off by the small motor; after the regular oil was re-

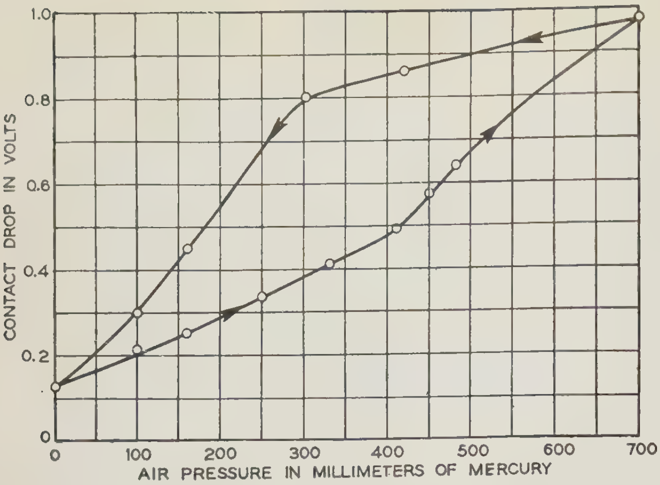


Fig. 5. Variation of contact voltage drop with air pressure, at low current density

Graphite brush on copper ring; current 0.15 ampere; brush area 0.125 square inch; brush polarity negative

placed by an oil having an extremely low vapor pressure, the trouble disappeared.

The contact drop at lower current densities is especially sensitive to anything that reduces the rate of oxidation. For instance, the normal contact drop of the small copper ring in air at 1 ampere was 0.48 volt, which was reduced upon the introduction of an oxygen-free gas (commercial nitrogen) to 0.053 volt, or a reduction in contact resistance in the ratio of 9 to 1. At a current of 2 milliamperes, the change was from 0.2 to 0.0003 volt under the same condition, or a reduction in contact resistance in the ratio of 670 to 1.

In figure 5 is shown a curve of contact drop at low current density plotted against air pressure around the contact. The peculiar shape of the curve is difficult to understand. The starting point is at the lower left-hand corner and the contact had been running overnight with an air pressure of 0.2 millimeter of mercury. To obtain the lower branch of the curve the vacuum pump was shut off and a small leak was produced such that the air pressure around the contact rose in 20 hours to within about 2 centimeters of atmospheric pressure. The curve was plotted from readings of contact drop and air pressure. The return loop or upper curve was obtained by reducing the pressure in steps, with the contact operating about an hour at each pressure. The fact that the upper half of the curve does not coincide with the lower half is probably attributable to some time lag effect, the lag growing less as the pressure is reduced below 300 millimeters. It is important to notice that the decrease in contact drop when the air pressure is reduced to a very low value is not as great as when the air normally surrounding the contact is replaced by an oxygen-free gas. The difference is probably greater than the reader at first will realize, as the data for the curve of figure 5 were taken with the brush negative (current flowing from the ring to the brush), and the reduction in contact drop effected by an oxygen-free atmosphere is greater with this polarity than with the opposite polarity. The difference may be attributable to contamination of the ring surface by spurious vapors when the contact is operating at low pressure. It is practically impossible to obtain a clean condition in a vacuum system containing a motor with insulation and with the small amount of volatile oil that always must be present. Observations on a small gold surfaced ring as the air pressure was reduced around the contact, showed sometimes as much as a threefold increase in contact drop over its normal value in air at atmospheric pressure. This certainly was caused by contamination, as just described, for the low contact drop could be restored simply by washing the ring and brush with carbon tetrachloride.

Contact Drop With Different Ring Materials

All base metals such as copper, iron, nickel, and others, oxidize when exposed to the air, even at room temperature. The first layers of oxide form very rapidly; but since these first layers act to protect the metal of the ring, the rate of growth of the film continually decreases so that years might be required for it to grow to a thickness of 10^{-5} inch. At temperatures of the order of 100 degrees centigrade the same film can be produced in a few hours, and at higher temperatures of course in even shorter times. The figure of 10^{-5} inch is just about the thickness of the familiar brown film seen on commutators that have been in service for some time.

The noble metals oxidize much less readily. Of platinum, gold, and silver, only silver oxidizes appreciably at room temperature or any higher temperature. The difference between the noble and the base metals can be explained best by reference to figure 6, the curves of which are plotted from previously published data.[7] These curves indicate the dissociation pressures of the oxides of several metals, the dissociation pressure of an oxide being the pressure of oxygen that will build up in equilibrium with the oxide if it is sealed in an evacuated tube. This method of determining dissociation pressures is, however, not practical for the base metals (copper, nickel, iron, etc.), and the curves for these metals were obtained by calculation. The dissociation pres-

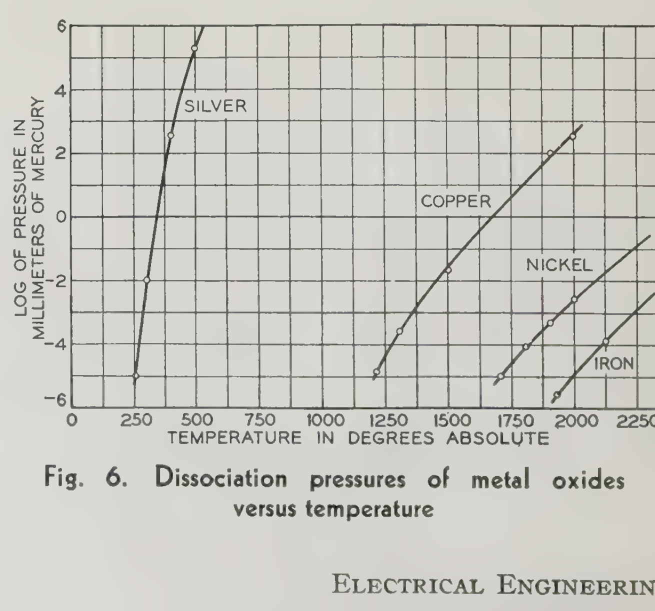


Fig. 6. Dissociation pressures of metal oxides versus temperature

sure of an oxide is very similar to the vapor pressure of a liquid. If the partial pressure of oxygen in the atmosphere surrounding the oxide is greater than the dissociation pressure of the oxide at the particular temperature, the oxide is stable; and if any of the metal of the oxide is present, it will be oxidized. If, however, the partial pressure of oxygen is lower than the dissociation pressure of the oxide, the oxide will be reduced to oxygen and the metal. An observation of the curves of figure 6 shows that even in a very good vacuum, the temperatures necessary for the decomposition of the oxides of copper, nickel, and iron are higher than the melting points of these metals. The temperature indicated by these theoretically deduced curves are apparently a little high, for it is common practice to clean up these metals in a good vacuum at temperatures somewhat lower than the melting point; but the discrepancy is not great enough to make any difference in this discussion. In any event, it obviously would be impossible to remove completely the oxides of these metals simply by heating in air. The rate of oxidation can be reduced, however, by limiting the amount of oxygen at the surface; and in a sliding contact where the ring is being abraded continually by the brush, this will result in a decreased contact drop.

The oxide of silver, as may be seen from the curve of figure 6, is reduced much more easily. Even in air (partial pressure of oxygen approximately 15.2 centimeters), silver oxide will decompose at a temperature of 375 degrees absolute (102 degrees centigrade). Thus, it is possible by heating a piece of silver to this temperature to remove the oxide completely from its surface. This fact will be demonstrated a little later by showing how the contact drop characteristic of a silver ring changes when the ring is heated.

The curves for platinum and gold lie still further to the left in the system of curves shown in figure 6, and slip rings of these materials are free of oxide even at normal operating temperatures.

Some volt-ampere curves obtained on a gold ring, a silver ring, and a carbon ring are shown in figure 7. The oxide of carbon is gaseous and, therefore, has no insulating effect in the contact. The resistance of the contact on this ring is, therefore, low and independent of current in the range of currents used. The gold ring is free of oxide at the normal operating temperature, and its contact resistance is low and also independent of current density. The silver ring at normal operating temperature forms an oxide film on its surface, and under this condition its contact drop at 5 amperes was about 0.25 volt. Its volt-ampere characteristic under this condition was found to be concave downward. The curve for the silver ring

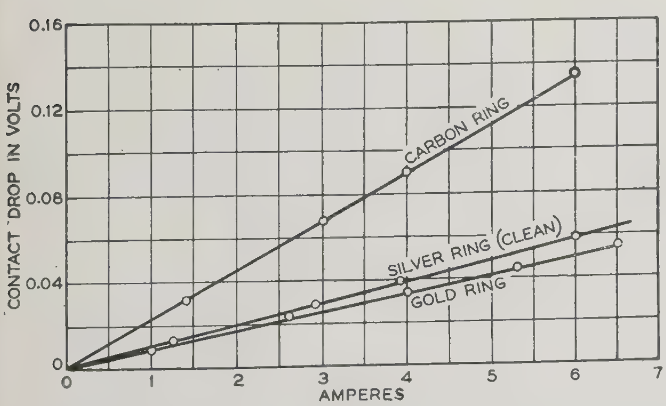
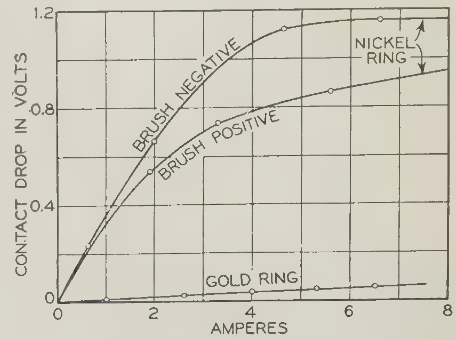


Fig. 7. Contact voltage drop versus current for graphite brush and carbon, gold, and silver rings

Brush area 0.125 square inch

Fig. 8. Contact voltage drop versus current for graphite brush on nickel and gold rings

Brush area 0.125 square inch



shown in figure 7 and marked "(clean)" was taken after a gas flame had been played over the surface of the ring to heat it to a temperature of about 90 degrees centigrade. This was apparently high enough to reduce the oxide on the ring, and bring the contact resistance down to the low value indicated by this curve. A similar heat treatment of the copper ring reduced the contact resistance only slightly, and the shape of the volt-ampere curve after the treatment was still the familiar downward concave or drooping characteristic commonly observed.

Figure 8 is included only to show the tremendous difference between the contact drop on a gold ring and on a nickel ring. It may be seen that the characteristic of the contact on the nickel ring is quite similar to that commonly observed on a copper or iron ring (oxide-carrying ring) whereas the characteristic for the gold ring (oxide-free ring) is a straight line.

Thermal Voltage in a Sliding Contact

To determine the thermal voltage appearing in a sliding contact, a simple test was set up as shown in figure 9. The arrangement consists of a copper ring 3 inches in diameter driven by a small variable-speed motor. A graphite brush, previously worn in with current flowing, rode on the surface of the ring and was connected to one side of a potentiometer. On the side of the copper ring was fastened a plate of graphite on which rode a small brush of the same material. This brush was connected to the other side of the potentiometer.

With the ring still and all parts of the apparatus at the same temperature, the net thermal voltage for the system was practically zero. When the ring rotated, however, the friction at the small points of contact between the ring and the brush heated these points to a degree depending upon the speed of rotation, and it was possible to obtain a curve between

the speed of rotation and the thermal voltage generated. The thermal voltage followed the ring speed very closely, that is, there was no appreciable time lag of the thermal voltage when a change in speed was produced. This would be expected for the small areas of contact between the brush and the ring heat and cool very rapidly.

During the test, all points of discontinuity in the system remained at essentially the same temperature except the contact between the copper ring and the graphite brush riding on it. It is obvious, therefore, that the thermal voltage observed was generated in this contact. A temperature rise in this region would produce a thermal voltage at the graphite-copper oxide junction and also at the copper oxide-copper junction, and only the differential of these 2 voltages would be observed by the method of measurement used. The net voltage observed had the polarity of the copper oxide-copper junction.

Assuming that the coefficient of friction between the brush and ring is independent of the speed of rotation of the ring, the energy converted into heat per revolution is fixed and the amount of heat generated at each little point of contact will be independent of the speed of rotation. The heat generated at any small area, however, will flow rapidly away from the point of generation into the brush and the ring, and the temperature rise at the contact points, therefore, will be inversely proportional to the time a point of

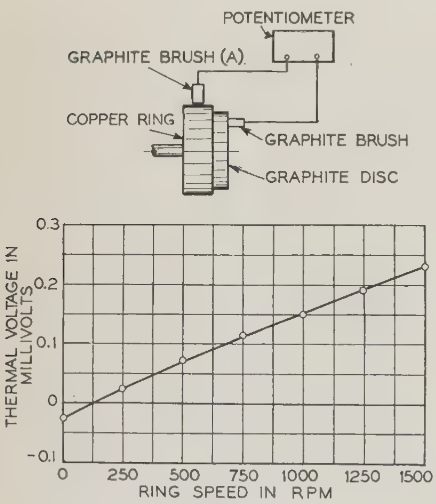


Fig. 9. Thermal voltage in a sliding contact

For positive voltages brush polarity is negative and ring positive

contact is in use, or directly proportional to the speed of rotation. This explains the linearity of the curve shown in figure 9.

Sanding the ring surface caused the thermal voltage to disappear, for this removed the oxide film and established practically metallic contact between the brush and the ring.

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Automatic Control for Mercury Arc Rectifiers

Automatic control for steel-tank mercury-arc rectifiers may be considered under 2 main divisions, one being control for switching equipment, and the other being control of the unit auxiliaries such as tank heaters, anode heaters, vacuum control and protective equipment, arc ignition and excitation, cooling tank, and circulating pump. A review of present day practice in automatic control for mercury arc rectifiers is presented herewith.

By
H. BANY
ASSOCIATE A.I.E.E.
General Electric Co., Philadelphia, Pa.

M. E. REAGAN
MEMBER A.I.E.E.
Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

THE development of the steel tank mercury arc rectifier has progressed to such an extent that its inherent advantages for the conversion of alternating current to direct current are gaining greater recognition each succeeding year. On account of its higher efficiency at the higher d-c voltages, it is particularly well adapted for railway service, where 600 to 3,000 volts direct current are the common voltages, and it is here that the mercury arc rectifier has found its greatest application. By use of anode grid control, rectifiers can also be made to function as inverters and have been applied to railroad electrification where regenerative braking is necessary. Due to other desirable characteristics, including the ease of d-c voltage adjustment by

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grid control, their use is continuing to increase for the lower voltage industrial applications.

It is not the purpose of this discussion to deal in any detail with the new developments or technical aspects of the rectifier itself. However, since the use of this type of conversion apparatus has become so general, and since most of the installations are unattended, it is felt that a presentation, or résumé, of present-day control methods for steel tank mercury arc rectifiers is quite timely and would be of interest to those who are using or contemplate the use of such apparatus. Views of steel-tank mercury-arc rectifier installations are shown in figures 1 and 2.

The Mercury Arc Rectifier

In order to treat the subject of the control more logically, it is desirable to review briefly the fundamental operating requirements of the mercury arc rectifier itself.

The valve action of the rectifier results in current flow from the main anodes (of which there usually are 6 or more in a modern tank) to the cathode. This action depends upon maintaining the foreign gas pressure and the temperature of the rectifier tank within the given operating limits and upon proper ignition and subsequent holding of the arc, or excitation, from auxiliary anodes.

In order to attain the extremely low value of foreign gas pressure (0.1 to 3.0 microns of mercury) required during normal operation, an exhaust system, consisting of a mercury condensation pump, interstage reservoir, and rotary vacuum pump, is provided. In addition, to secure the proper elimination of air from the pores of the metal parts when the tank is initially placed in operation, or upon reassembly after having been subjected to atmospheric pressure, there is provided the necessary degassing equipment to apply heat to the anodes during this time. This consists of a so-called degassing, or loading, transformer, or low voltage taps on the main transformer, and a loading resistor.

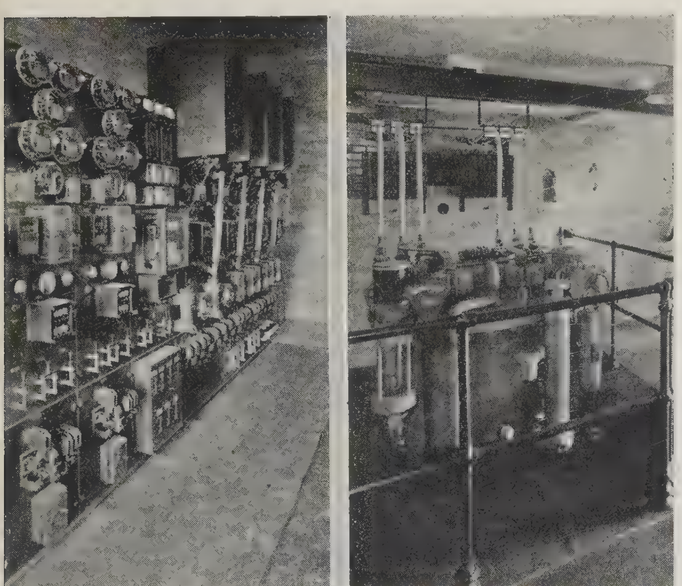

Fig. 1. Interior views of a 2-unit rectifier substation for street railway service

To hold the rectifier temperature below the limiting value, a circulating cooling system must be provided, and to hold it above the limiting value, electric tank heaters, or anode heaters, or both are generally necessary in all but tropical climates.

The arc ignition is accomplished by means of an arc striking or ignition anode and solenoid, and the holding or excitation arc is maintained by the required number of auxiliary excitation anodes.

The necessary surge suppressors must be provided across the transformer windings to prevent serious overvoltage at the time of a fault when the rectifier arc is extinguished. Filters or resonant shunts for preventing telephone interference may in some cases be required.

The rectifier must be disconnected from the system in case the foreign gas pressure becomes too high, the tank temperature becomes too high or too low, on d-c short circuit and continued overload, on arc back, and usually also on low or on single-phase voltage supply. An arc back results from the failure of the valve action of one or more anodes and is thus a short circuit between anodes inside the rectifier tank.

A-C Primary Equipment

The a-c primary equipment, including oil circuit breaker and disconnecting means, power transformer, lightning arresters, control power transformer and instrument transformers, is similar to that required for the usual rotating machines, except as mentioned below, and with the further exception that in no case is any equipment for reduced voltage starting required.

The oil circuit breaker must primarily be chosen to meet the system interrupting capacity requirements. However, due to the characteristic of the mercury arc on circuit interruption which results in a high recovery voltage rate, it is advisable, particularly on the higher a-c voltages, to favor a circuit breaker with more effective means of circuit interruption than plain break type of contacts, even though such a breaker would otherwise not be required for a-c system interrupting capacity requirements. Circuit breakers with circuit interrupting time of 0.15 to 0.20 second, measured from the instant the trip coil is energized, are usually satisfactory to prevent possible damage to rectifier parts and excessive evolving of gas. Means for tripping the breaker vary with the application. Overcurrent tripping features, using either a-c current trip coils or d-c potential trip coils must be provided, as required for opening any a-c breaker on overcurrent. However, the use of a direct acting undervoltage device on the oil circuit breaker mechanism to insure its tripping out immediately on failure of a-c power is usually not required.

The power transformer must necessarily have the proper design characteristics for the rectifier to suit the application and have the required connections with or without interphase transformers. Generally

some form of temperature measuring device is included to function on excessive temperature as might be caused by continued overload.

As with synchronous converters, fuses may be substituted for the high voltage oil circuit breaker, in special cases. To show any economy, however, the rectifier unit must be of small capacity or in service most of the time so that the no-load losses of the power transformer do not exceed the saving resulting from this substitution. The absence of the high voltage breaker further requires that a breaker be installed in the secondary or anode leads to open before the fuses can blow in case of arc-backs and when the unit is shut down. Since this requires one pole per anode, there may be no over-all saving.

Instrument Equipment

Following is the usual recommended instrument and meter equipment.

Alternating Current

1 voltmeter (one required per installation).
1 ammeter (may be optional).
1 watt-hour meter (may be optional).

Rectifier

1 vacuum indicator.
1 ammeter in vacuum indication circuit (optional).
1 ammeter in excitation circuit (optional).

Direct Current

1 voltmeter (one required per installation).
1 ammeter.

Control Power

The control or auxiliary power requirements of an automatic rectifier installation can be divided into 2 parts. One part consists of the power required for the unit auxiliaries for such purposes as the tank heaters, anode heaters, vacuum control and protective equipment, arc ignition and excitation, cooling fan, and circulating pump. The other part consists of the power required in the automatic switchgear for purely control and tripping purposes.

Control Power for Unit Auxiliaries

The rectifier auxiliaries require the greater amount of power, and a bank of 2 control power transformers with 220 volt secondaries connected open delta is the usual source of supply. If there is available for this purpose a separate satisfactory and dependable low voltage a-c source, this can be used. The use of a control battery for this part of the control power is neither necessary nor desirable.

Insulating transformers are required to isolate the control of those rectifier auxiliaries that are at the potential level of the rectifier tank (which in a grounded negative railway system is on the ungrounded side) from the other devices not at this potential level. Such auxiliaries are the arc ignition and excitation circuits, the tank jacket and anode heaters, the temperature regulating and protective relays, the vacuum relay and pumps, and the water circulating pump and blower motors in a closed cooling system. On d-c voltages of 600 volts and below the arc ignition and excitation circuits are usually supplied from one insulating transformer bank, while the other devices are isolated by an additional bank. It is the usual practice, however, on these lower voltages not to segregate the one group of these devices from the other on the switchboard. On d-c voltages above 600, it is usually desirable to incorporate additional small insulating transformers in the equipment for isolating the tank temperature protective devices and vacuum protective relay contacts from the control, indication, or alarm circuits. In addition, on these higher voltage equipments—particularly 3,000 volts d-c and above—it is usual to isolate those devices at tank potential from the other devices in the equipment not at this potential, either by segregation on a common switchboard or by mounting them on a separate panel adjacent to the rectifier itself. The desirability of isolating these circuits electrically thus makes a-c control power, with which this can be accomplished quite simply by insulating transformers, inherently more suitable than direct current for these auxiliaries.

Three phase control power is generally used because 3 phase squirrel cage induction motors are better adapted to the larger motor drives for the circulating water pump and blower in a closed cooling system than are single phase motors. Single phase motors are, however, somewhat simpler to control and protect, and therefore are generally used for the smaller auxiliaries. Three phase control power also may be required for rectifiers provided with a-c excitation. When 3 phase control power is present, the single phase load, such as single phase motors and heaters, is distributed between phases so as to obtain most nearly balanced load conditions.

Control Power for Switchgear

The control power for the automatic switchgear can also be 220 volts alternating current and supplied from the same control power transformers that are used for the rectifier auxiliaries. In order to prevent momentary voltage dips down to about 50 per cent of normal a-c voltage from tripping off the unit, the a-c undervoltage relay is provided with a time delay on drop-out. This relay is generally set with a pick-up of about 85 per cent and a time delay drop-out of 80 per cent. On voltage dips down to less than 50 per cent of normal—which approach the instantaneous drop-out value of the master contactor and other control devices—there is the possibility of tripping off the unit at this time. Since the rectifier can be placed back on the line immediately after such an outage, the momentary tripping off of the rectifier is usually not objectionable.

With a control battery, the rectifier will not be tripped off the line until the expiration of the drop-out time of the a-c undervoltage relay. A control battery further provides a more flexible and reliable source of control power, and so in the average base load installation it is usually advantageous to provide one. In case a dependable tripping source is the only requirement, a tripping battery not less than

24 volts direct current and preferably 48 volts direct current is recommended. However, in the simpler station layout without sensitive or special protective tripping features for the a-c incoming lines or transformers, and where the somewhat greater service continuity obtained is not so important, a-c control power (supplied by control power transformers connected to the a-c incoming line or a-c bus), ahead of each rectifier transformer oil circuit breaker, is generally satisfactory for all the control power.

Vacuum System Control

In order to keep the tank *pressure* at the desired minimum, the proper control must be provided for the exhaust system. The mercury condensation pump, with a heater energized from the a-c control and insulating transformer circuit, and operating on the steam injector principle, is in continuous operation, exhausting the gases into the interstage reservoir located between it and the rotary vacuum pump.

The mercury condensation pump is provided with cooling coils, and the cooling medium is obtained either from the same cooling system used for the rectifier tank, or from a separate one, where it is advantageous to do so in the case of a closed cooling system. Protection is provided to disconnect the heater from the circuit on failure of flow of the cooling medium.

The rotary vacuum pump may be controlled by the pressure in the interstage reservoir, which must be kept below approximately 1,000 to 3,000 microns of mercury in order to give efficient operation of the mercury condensation pump. In this case a manometer, dependent upon interstage reservoir pressure, controls the vacuum pump motor direct, and a separate vacuum relay, dependent upon rectifier tank pressure, is used in the master control contactor circuit to permit connecting the rectifier to the a-c and d-c power circuits only within the proper limits of foreign gas pressure. This vacuum relay is provided with a pointer and scale and thus serves as a visual instrument also. It operates on the change of current in a compensated bridge circuit. One arm of this bridge circuit consists of a resistor, in communication with the vacuum chamber of the rectifier. Its resistance is dependent upon the rate of flow of heat through the surrounding space, which in turn is a function of the foreign gas pressure in the vacuum chamber, and thus the current in the vacuum relay coil circuit connected across the bridges varies with the foreign gas pressure in the tank. A control diagram of this scheme is shown in figure 3*b*.

The rotary vacuum pump may also be controlled by the rectifier tank vacuum relay itself, combining the vacuum pump and rectifier control functions into one device. However, when rectifier foreign gas pressure is used directly to shut down the rotary vacuum pump, a time delay is interposed, after the desired tank pressure is reached, so that the interstage reservoir will be exhausted sufficiently to allow the mercury pump to operate at its most efficient point. A control diagram of this scheme is shown in figure 3*a*.

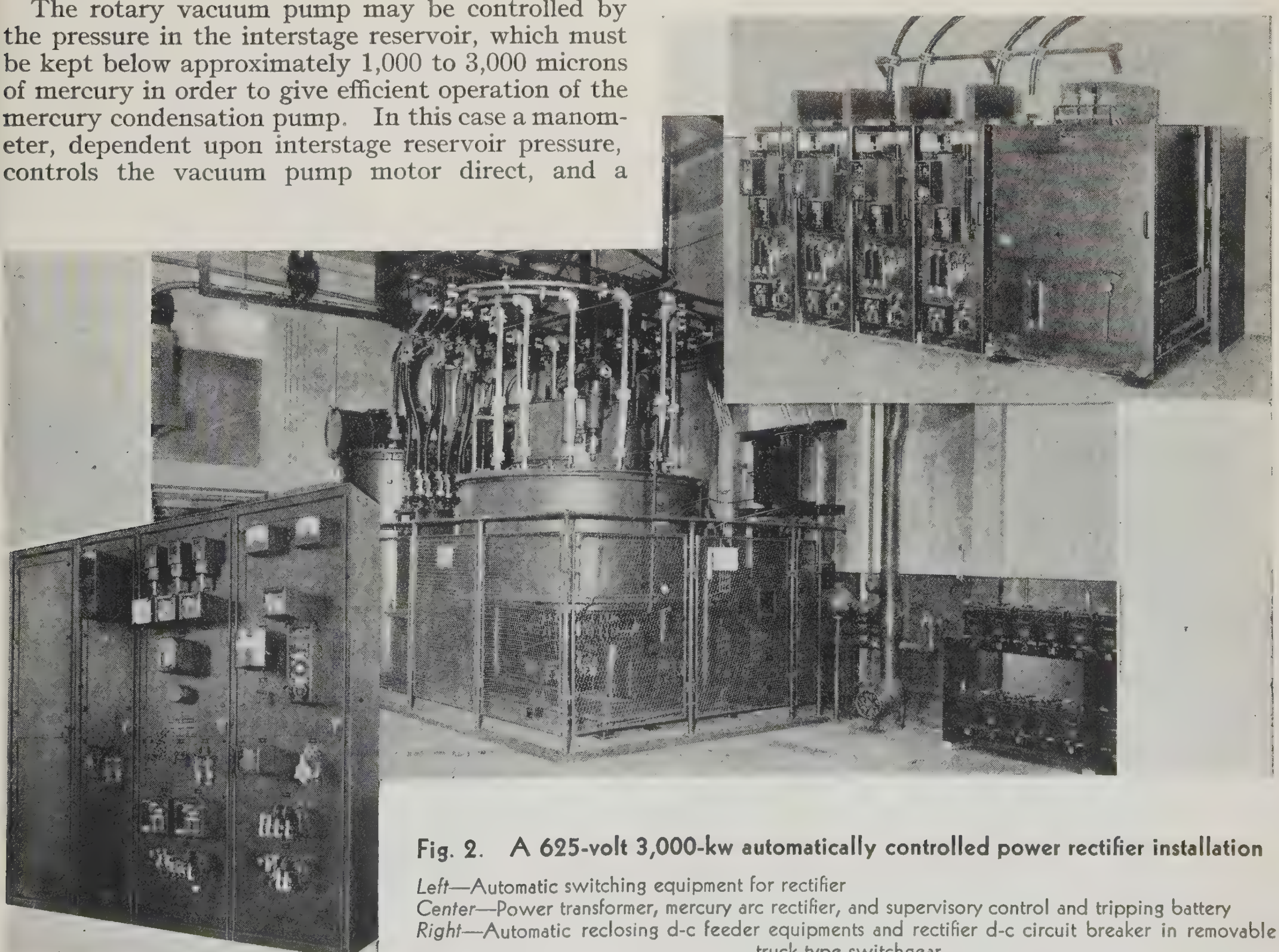

Fig. 2. A 625-volt 3,000-kw automatically controlled power rectifier installation

Left—Automatic switching equipment for rectifier
Center—Power transformer, mercury arc rectifier, and supervisory control and tripping battery
Right—Automatic reclosing d-c feeder equipments and rectifier d-c circuit breaker in removable truck type switchgear

By using a smaller design of rotary vacuum pump, this pump may be left in operation continuously, and so the starting and stopping control of this pump may be dispensed with entirely. In any of the above arrangements, however, it is necessary to use an automatically operated check valve between the interstage reservoir and the rotary vacuum pump, to prevent air and oil being drawn into the rectifier tank, whenever the rotary vacuum pump is not operating.

Tank Temperature Control Equipment

In order to hold the rectifier *temperature* within the limits for successful operation, the cooling system (which may be one of serveral different types) and the tank and anode heaters must be controlled by the necessary thermal or load responsive devices.

The simplest cooling arrangement is the open system or tap water cooling, which is used where the available tap water is sufficiently free from impurities to make this permissible. Figure 4*a* shows the schematic layout for this type of system. The flow of the water is controlled by the thermo-responsive regulating valve, whose thermo-sensitive bulb is located at a point in the tank water jacket best suited for controlling the temperature in the anode region. The heaters are controlled by a thermo-responsive relay, whose thermo-sensitive bulb is located in the tank water jacket.

When the tap water available is not sufficiently free from impurities to use in the rectifier water jacket—so that, due to excessive corrosion and sediment, cleaning and possible replacement of the jacket would be necessary—a closed cooling system with a water-to-water heat exchanger may be used. A motor driven pump circulates the cooling medium through a storage tank, the heat exchanger, and the rectifier water jacket. Tap water, whose flow is controlled by a thermo-responsive valve with its bulb located in the rectifier tank jacket, is used to absorb and carry away the heat from the heat exchanger. As in the open system, a thermo-responsive relay controls the heaters, which may be located in the rectifier tank jacket, or in the system storage tank.

A common arrangement of closed cooling system uses an air surface cooler instead of a water-to-water heat exchanger. The surface cooler is provided with a motor-driven radiator fan which is in operation only when the unit is carrying load, or when the temperature of the cooling medium exceeds a given value. To allow for seasonal temperature variations, or variations in load or operating conditions, the fan motor may be provided with pole changing switches so that the amount of cooling obtained best suits these conditions. The flow of the cooling medium by means of the circulating pump and the energization of the heaters are controlled as in the previously mentioned systems. Figure 4*b* shows a schematic layout for this system.

The advantages of a closed cooling system are that the purity of the cooling medium can be controlled, and better rectifier performance is obtained due to the maintenance of a more uniform temperature in all parts of the rectifier tank. The system using the

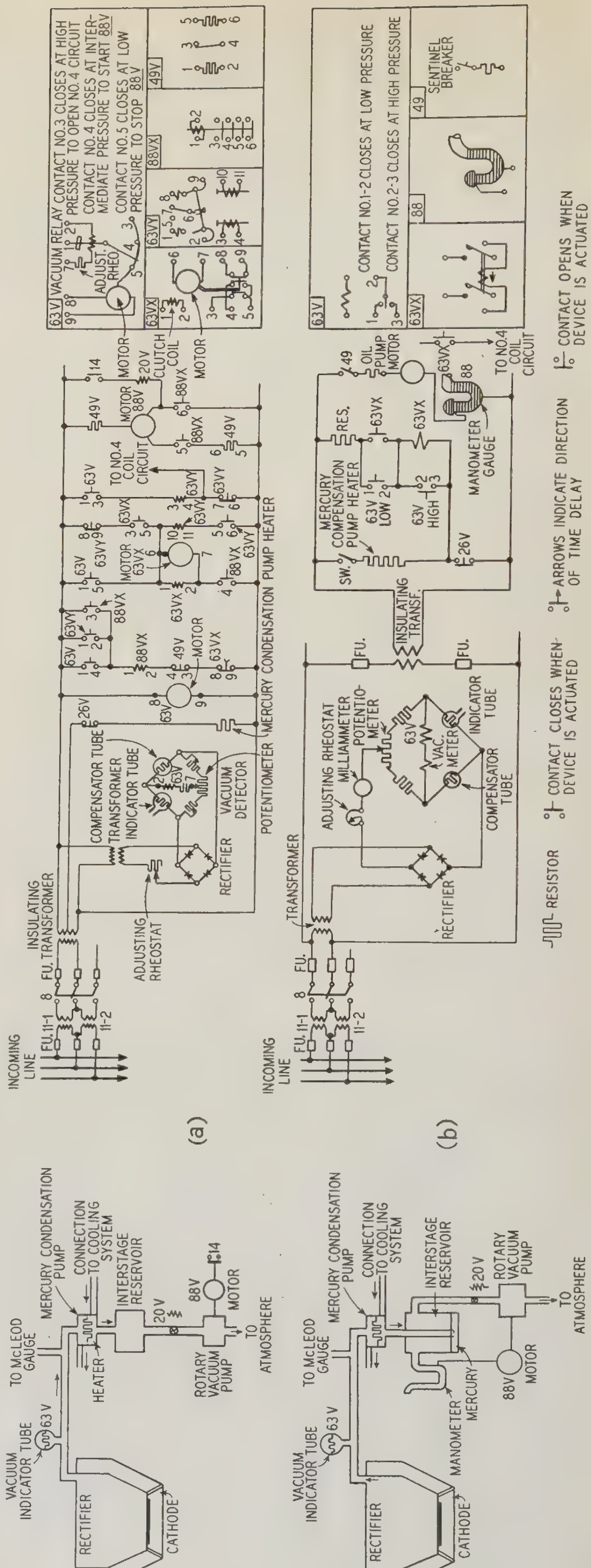

Fig. 3. Schematic diagrams of exhaust system (left) and of vacuum control and protective circuits (right)

a—Vacuum pump controlled by rectifier tank vacuum relay
b—Vacuum pump controlled by pressure in the interstage reservoir
For meaning of symbols, see table I

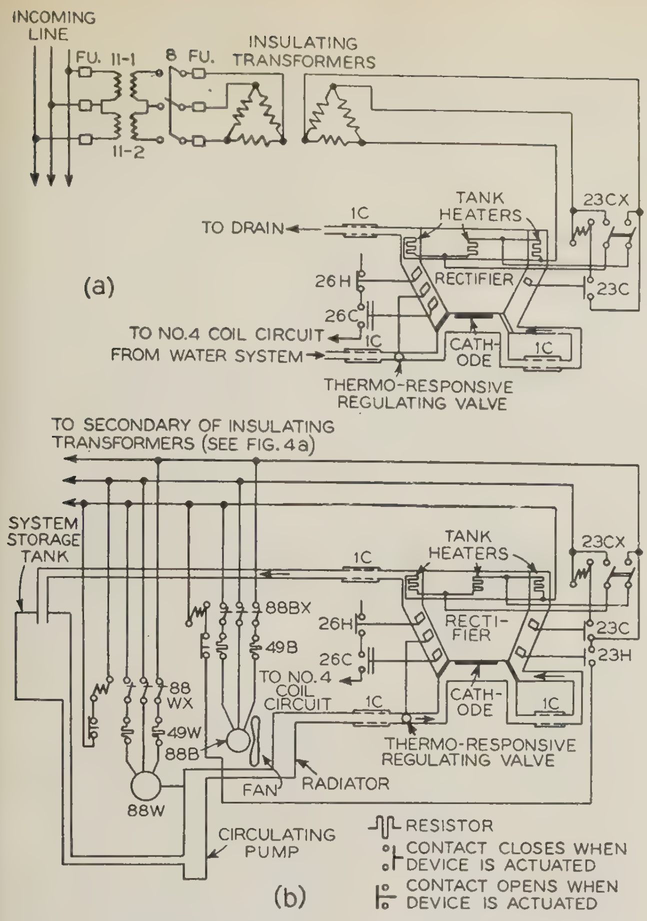

Fig. 4. Schematic diagrams of temperature control equipment

a—Open system *b*—Closed system
For meaning of symbols, see table I

surface cooler has the further advantage of being completely self-contained, and can be more readily protected against freezing where necessary.

Anode heaters, or anode jacket heaters, may be required in certain cases to hold the temperature of the main anodes above a limiting value, and thus prevent the possible condensation of mercury on them, causing an arc-back. Such anode heaters are usually controlled by an undercurrent relay, operating from a current transformer in the a-c side of the rectifier power transformer, and the anode jacket heaters are usually controlled by a thermostat located in the anode water jacket.

Master Element Used for Giving Starting Indication

In order to have the rectifier ready for operation at any time, the vacuum and temperature regulating equipment must be in service at all times. Therefore, these functions are not dependent upon the control of the master element which places the rectifier in operation.

The type of master element used is dependent upon service requirements, as in the case of all other types of automatic installations, and may be either one or a combination of devices or functions as follows: low d-c bus voltage after time delay, time switch, local or remote push button or switch, supervisory control, overload on preceding unit, or failure of preceding unit. The opposite indication of the master element, of course, takes the unit out of service immediately or after time delay.

With the increasing use of supervisory control, particularly for base load stations for railway service, most of the later installations have used this form of starting and stopping, together with telemetering equipment to inform the load dispatcher of d-c voltage and load conditions.

Master Contactor and Closing of A-C Circuit Breaker

The master element usually controls a master relay or contactor, which, when it closes, places the rectifier in operation and connects it to the a-c and d-c systems, and when it opens, disconnects it from the circuit and shuts it down.

In addition to the contacts of the master element, contacts of the necessary protective devices are in the master relay or contactor coil circuit, to prevent starting, and also subsequently, when necessary, to cause temporary or lock-out shutdowns as required by the nature of the abnormal condition or fault.

All of the protective devices which cause temporary or lock-out shutdown prevent starting or restarting until the abnormal condition has been corrected.

Table I—Nomenclature Used in Figures 3 to 7

Function No.	Nomenclature	Function No.	Nomenclature	Function No.	Nomenclature
1	Master element	27	A-c undervoltage relay	72	D-c line circuit breaker
2	Time delay starting relay	28	Load shifting resistor thermal device	73	Load shifting resistor circuit breaker
4	Master contactor	31	Ignition anode	76	D-c overcurrent relay
5	Stopping device	37	Undercurrent relay	79	A-c reclosing relay
8	Control power switch	49	A-c thermal relay (power transformer)	86	Locking out relay
11-1, 11-2	Control power transformer	49*B*	A-c thermal relay (blower motor)	88*B*	Blower motor
14	Underspeed device	49*V*	A-c thermal relay (rotary vacuum pump motor)	88*V*	Rotary vacuum pump motor
20*V*	Solenoid operated vacuum valve	49*W*	A-c thermal relay (circulating pump motor)	88*W*	Circulating pump motor
22	Equalizer contactor	51	A-c overcurrent relay	89	Line switch
23*A*	Anode temperature regulating relay	52	A-c circuit breaker	93	Excitation changing contactor
23*C*	Tank temperature regulating relay (cold)	53	Excitation relay	152	A-c circuit breaker
23*H*	Tank temperature regulating relay (hot)	62	Time delay stopping relay	172	D-c circuit breaker
26*C*	Tank temperature protective relay (cold)	63*V*	Vacuum relay	*AM*	Ammeter
26*H*	Tank temperature protective relay (hot)	63*W*	Water flow relay	*Fu*	Fuse
26*V*	Mercury condensation pump protective relay	64	Grounding protective relay	*I.C.*	Insulating connection
				Res.	Resistor

The closing of the master contactor immediately causes the a-c line oil circuit breaker to close, energizing the rectifier power transformer.

Arc Ignition and Excitation

Then the ignition transformer is energized and the solenoid of the arc-striking anode is energized, causing this anode to be dipped into the mercury cathode pool. When the anode touches the mercury, this short-circuits its operating solenoid, causing it to be withdrawn immediately by means of its spring. In so doing it draws an arc which is transferred to and maintained by the excitation anodes, supplied from the excitation transformer. The establishment of the excitation arc causes the main anodes to fire and d-c voltage to appear on the cathode. A typical circuit for one scheme employing 3 phase a-c power is shown in figure 5*a* and a variation of this scheme using single phase a-c power is shown in figure 5*c*.

In certain cases where the rectifier may operate at a very small percentage of rated load, and where maximum continuity of the main arc is essential at all times, the control equipment automatically causes the excitation current to be increased at loads below about 10 per cent of normal. This is usually accomplished by having an undercurrent relay in the rectifier circuit close a contactor that shunts a current limiting reactor in series with the excitation transformer.

Another ignition and excitation scheme, using direct current obtained by means of a copper oxide rectifier, causes the arc to be established in a manner similar to that described above. A typical circuit for this arrangement is shown in figure 5*b*.

D-C Circuit Breaker and D-C Overcurrent Protection

When the main anodes fire, full d-c voltage appears on the rectifier cathode, causing the d-c line circuit breaker to close, energizing the d-c bus directly or through load limiting or load shifting resistors.

The use of load shifting resistors in the usual 600 volt or 1,500 volt d-c railway unit is governed by the same general considerations as govern a synchronous converter installation except that there is somewhat less reason for using as much resistance for the protection of the rectifier itself. A rectifier can take care of relatively high momentary overloads, and does not have the definite commutating limitations of a rotating machine. Hence, resistors are used primarily for load shifting rather than definitely for load limiting, and therefore for momentary overload protection one step of resistance to give about 10 per cent voltage drop at full load is considered satisfactory for the average installation. Where a second step is necessary for more severe service conditions, an additional 15 per cent voltage drop at this same load is usually sufficient. The thermal rating of the resistor generally is based upon carrying $1^1/_2$ times rated load for 5 minutes at not over 350 degrees centigrade rise. The overcurrent device used for inserting each step of resistance may be an a-c relay operating from current transformers in the a-c side of the rectifier power transformer, or a d-c relay operating from a shunt in the d-c side, or it may be a self-contained overcurrent trip incorporated in the load shifting resistor shunting breaker. Reclosing upon reduction of the load can be accomplished either by suitable drop-out settings of the overcurrent relay or by a separate voltage relay connected across the load shifting resistance. As in all load shifting control

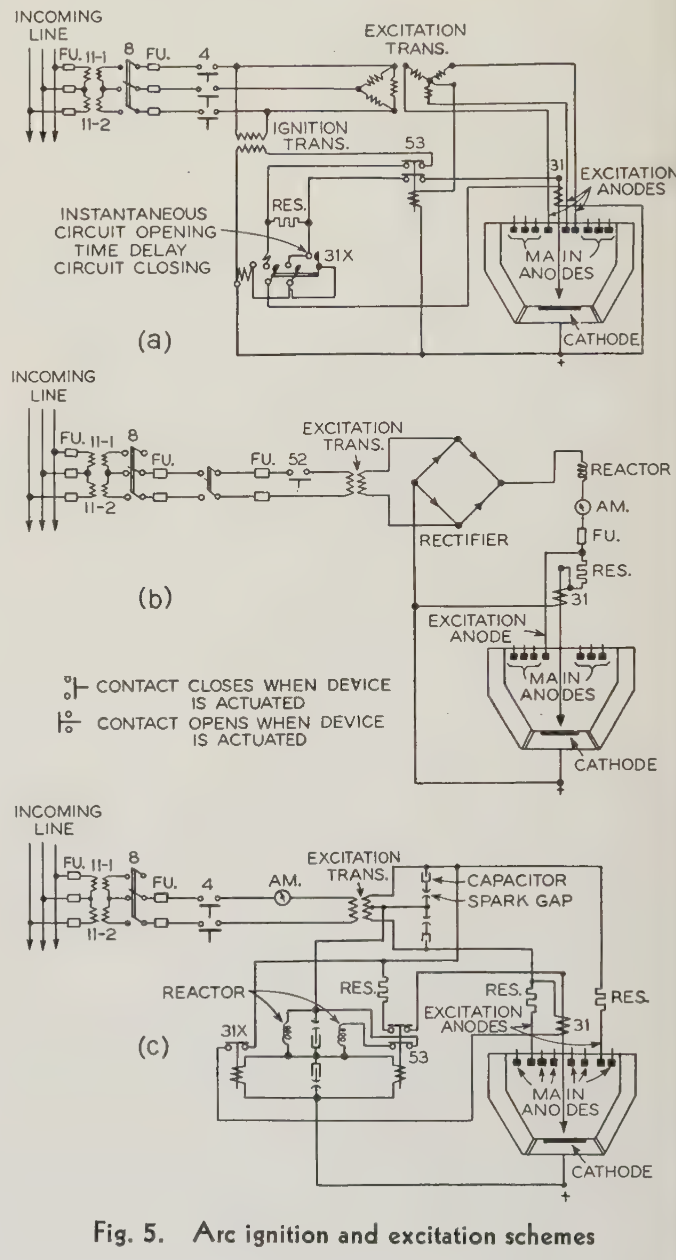

Fig. 5. Arc ignition and excitation schemes

a—Typical circuits for a scheme employing 3-phase a-c power

b—Typical circuits for a scheme using direct current obtained by means of a copper oxide rectifier

c—Typical circuit for a scheme using single-phase a-c power

For meaning of symbols see table I

schemes a time delay before reclosing, including an auxiliary time delay relay (if not incorporated in the overcurrent relay or in the load shifting resistor breaker itself) is used to prevent rapid "pumping" of the breaker at any time.

D-C Feeders, and Voltage Regulation

D-c feeders, although usually included with the substation equipment, are considered a part of the d-c distribution system. For unattended stations they are of the automatic load indicating reclosing type, and are identical in design with d-c feeder equipments usually furnished with any rotating machines for the same service.

Reduction of the d-c voltage for load shifting purposes can also be accomplished in special cases by the use of anode grid control. The rectifier can further by this means be given a predetermined sloping or flat voltage characteristic, as desired. Rectifier applications with voltage regulating features have been made for railway, industrial, and communication work. Automatic stations are in service in which mercury arc rectifiers are installed operating in parallel with existing rotating machines. By proper design of the rectifier transformer, the regulation of

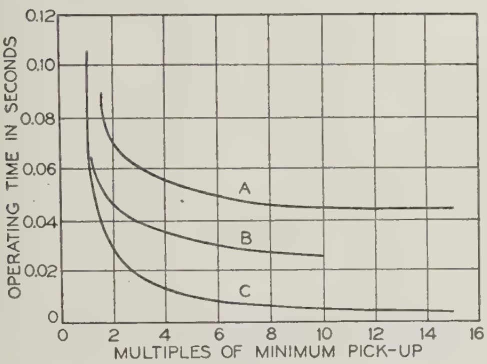

Fig. 6. Time-current curves for overcurrent relays

A—Short-time induction
B—Instantaneous plunger
C—High speed instantaneous plunger

the new unit is made to agree with the installed machine, resulting in successful parallel operation. To obtain a substantially flat voltage characteristic instead of the inherent slope, or to obtain other degrees of compounding, anode grid control affords a very flexible and satisfactory method of accomplishing this. Transformer tap changing may also be applicable in special cases.

In connection with the abrupt rise in the d-c voltage characteristic to about 15 per cent above normal at no load, for those installations with interphase transformers, operating conditions generally are such that no special provision is required in the design of the equipment to hold down this voltage, but where necessary this can be accomplished by the use of a small loading resistor controlled by an undercurrent relay.

Protective Tripping of the D-C Breaker

To give maximum protection against possible injury to rectifier parts due to back-feed from the d-c load circuit on arc-back, the d-c line circuit breaker is usually of the so-called high speed type, connected to trip in the direction of power flow into the rectifier cathode, and to open the circuit in about 0.01 to 0.015 second from the occurrence of the fault. However, dependent upon the specific application, in some 600 volt (d-c) installations and in most installations 300 volts and below, panel mounted switchboard type circuit breakers with a circuit interrupting time of approximately 0.05 second will give sufficient protection.

In the case of severe overload, or short circuit, tripping in the normal direction of power flow on the d-c line circuit breaker is not usual, since this protection should be incorporated in the d-c feeders or in the d-c load shifting resistor equipment when present, or in both. Protection on faults to ground inside the station may in some cases be afforded by a ground protective relay. The d-c breaker is usually opened immediately at any time the master contactor opens.

Protective Tripping of the A-C Circuit Breaker

In addition to the tripping of this breaker by the opening of the master control circuit and master contactor on normal or emergency shutdown, a-c overcurrent relays are provided to trip this breaker on rectifier arc-back, transformer faults, and d-c bus faults. These overcurrent relays should preferably have a slight time delay to give selective tripping of the d-c load shifting breakers or d-c feeder breaker on d-c overloads or short circuits, without giving an undesirably long time on tripping in case of arc-back. Tripping of the oil circuit breaker on arc-back in multiple feed installations may also be accomplished by means of "*b*" interlock (normally closed) contacts on the d-c circuit breaker, thus permitting the use of standard a-c overcurrent relays with longer time delay in this case.

The use of overcurrent relays with a slight time delay has the further advantage of not causing false tripping on the magnetizing transient whenever the oil circuit breaker is closed to energize the power transformer, thus eliminating the need for a special desensitizing connection for the overcurrent relays for this purpose. A characteristic curve of such a relay, which has been quite generally used, compared to present day instantaneous relays, is shown in figure 6.

Protective Devices

In case of a fault or other abnormal condition which would damage the unit if left in service or otherwise make it undesirable to keep the unit in operation, protective relays operate to take the equipment out of service, and to prevent its being restarted until it has been inspected. Where possible, and when there is no permanent fault inside of the station requiring human attention, other protective devices cause a temporary shutdown until conditions have again returned to normal.

The following abnormal conditions cause a temporary shutdown:

1. Low or single phase a-c supply voltage—by induction type a-c undervoltage and single phase protective relays.

2. Too high tank temperature—by thermostats mounted on the rectifier.

3. Too low tank temperature—by thermostats mounted on the rectifier.

4. Too high tank pressure—by the vacuum relay.

5. Single arc-back—by a-c and d-c overcurrent and reverse current protective devices. In this case, both a-c and d-c breakers open, but are permitted to reclose after a time delay. The master control contactor does not open. However, if subsequent openings of these breakers occur, or if either breaker does not reclose within a definite time, an opening and a lock-out of the master contactor will take place.

6. Failure of the cooling medium for the rectifier and for the mercury condensation pump—either directly by water flow relays or indirectly by rectifier and mercury condensation pump heater thermostats.

7. Transformer over-temperature due to sustained overload—by a relay operating on embedded temperature coils or hottest spot indicators in the transformers or by a replica type of relay.

8. Overheated load shifting resistors (when present)—by a thermostat located at the resistors.

The following conditions cause a lock-out shutdown until the protective device giving the indication is reset manually.

1. Succession of arc-backs—by a-c reclosing relay, covered by item 5 above.

2. Failure of rectifier to be connected to a-c and d-c system within a predetermined time—by a-c reclosing relay.

3. Failure of transformer cooling medium—by air or water flow relay (for air or water cooled transformers).

4. Severe a-c overcurrent—by a-c overcurrent relays and a-c reclosing relays.

Protection against starting of the auxiliary motors on a-c undervoltage is afforded by the a-c undervoltage and single phase protective relay. This device also affords protection against single phase starting of the 3 phase motors.

Protection in case of motor faults or short circuits is obtained by means of fuses, although such protection may in certain cases be provided for a group of motors rather than for each individual motor. Three phase motors should, in addition, be protected against single phase running.

Fault at *A*—Time of #51 relays must be longer than #172 opening (this time will be sufficient to cover transient when breaker #52 closes); #172 opens; #52 and #72 stay closed

Fault at *B*—#52 opens at end of timing for #51, or by #64; #172's open; #72 opens after #52

Fault at *C*—#72 opens, and *b* interlock or #51 opens #52; #172's stay closed

Fault at *D*—#52 opens from #51; #72 opens

Fault at *E*—#152 opens; no voltage opens #52 and #72

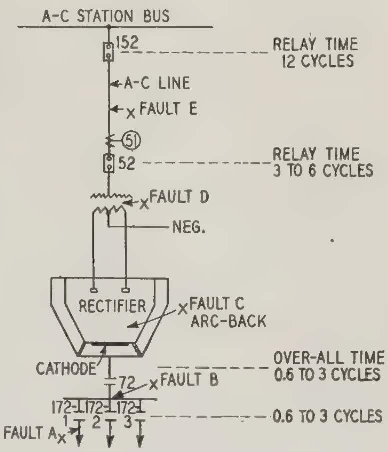

Fig. 7. Single phase line diagram of desired co-ordination of protective devices under various fault conditions

For meaning of symbols, see table I

A single line diagram showing the desired co-ordination of protective devices under various fault conditions is given in figure 7.

Adaptability for Automatic Control

Since the process of starting a mercury arc rectifier is inherently much simpler than for a rotating machine, because no reduced voltage starting equipment is required, and because there are no moving parts which require time to come up to speed, the control equipment for automatic starting is less extensive than that required for a rotating machine. Furthermore, certain automatic features of the control equipment, such as the tank pressure regulation, the tank and anode temperature control, and the ignition and arc holding circuits, are preferable even in a manually controlled station. The same is true of the associated protective features. Hence, the principal additional automatic features are electrical breaker closing mechanisms and the automatic reclosing relay to limit the number of reclosures of the a-c and d-c circuit breakers in case of trouble. Hence, to date, most rectifier equipments in this country have been furnished for unattended installations. Those that are not fully unattended, have generally been arranged for partial automatic control, with full automatic operation of the rectifier auxiliaries, so that an attendant merely closes or recloses the a-c and d-c circuits when required, and receives an alarm upon the occurrence of any abnormal condition that requires his attention.

Possible Future Developments

The foregoing is a résumé of present day practice in automatic control for mercury arc rectifiers. Due principally to future development possibilities in the rectifier itself, it may be expected that certain of these switching and protective arrangements may become modified or augmented to suit the change.

The further application of voltage control by anode grids and the increased use of rectifiers as inverters and as frequency changers should result in a gradual simplification of the present control methods for these less common rectifier applications. However, a further simplification of basic rectifier control and protective requirements appears to offer the best promise of simpler and less expensive automatic rectifier installations.

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Locomotive to Caboose Radio Communication

Although the characteristics of ultra-high frequency radio communication between fixed points have been established fairly well, the utilization of these frequencies in communication between front and rear of moving railway trains presented problems of which little was known. This paper reports the results of extensive tests made to determine the practical value of these frequencies for such service, and describes commercial equipment subsequently developed.

By
S. G. ELLIS
Membership Application Pending

Westinghouse Elec. and Mfg. Co., Chicopee Falls, Mass.

THE use of ultra-high frequency radio of limited power output for communication over short distances has been rapidly extending into many fields of activity. The purpose of this paper is to report on certain tests which were made to determine the practicability of communication between front and rear of freight trains by this means. Tests were conducted over a long enough period of time to experience all kinds of weather and other operating conditions. As might be expected a great many electrical and mechanical problems are encountered in such service that are not present when the sending and receiving points are stationary.

A paper recommended for publication by the A.I.E.E. committee on transportation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 28–31, 1936. Manuscript submitted Oct. 30, 1935; released for publication Dec. 6, 1935.

Experiments with many different methods of train communication have been tried in addition to the aural and visual signals now commonly employed. Among the more important of these are:

1. *Wired Telephone or Telegraph Communication.* Such a method, although possible, requires the equipping of each car on all railroad systems with a wire connection, couplings, etc. The installation expense, together with the fact that any break in the train interrupts communication, renders such a system impractical.

2. *Carrier Current Communication.* This system has been used successfully. However, it has a serious disadvantage in that it requires a wire parallel to the tracks throughout the entire railroad system.

3. *Radio Communication.* At the present time radio appears to be the best method of communication, giving as it does reliable service with a minimum of first cost and maintenance expense. In radio communication the use of high frequencies now is favored because of the likelihood that such frequency allocation can be obtained for this service.

Although the characteristics of ultra-high frequency between fixed points had been established fairly well, the utilization of these frequencies for mobile communication presented several problems about which little was known. Among these problems may be mentioned the following:

1. Transmitter power and receiver sensitivity required for normal train lengths.
2. Optimum carrier frequency.
3. Causes and magnitude of interference.
4. The best type and location of the transmitting and receiving antennas on the locomotive and caboose.
5. The special mechanical requirements for railway mobile radio equipment.

With the above problems in mind, Westinghouse engineers in conjunction with the railway operating personnel conducted a series of tests using radio telephone communication between locomotive and caboose on the main line of the New York, New Haven and Hartford Railroad between New Haven, Conn., and Springfield, Mass. This is a distance of 64 miles, and is through fairly level country. The work required approximately 18 months' time during which the apparatus traveled some 36,000 miles and was operated for approximately 1,500 hours.

The engine used during the tests was of the heavy freight service type equipped with automatic train

control. The caboose was of standard construction with a cupola in the center.

Description of Equipment

The first experimental equipment consisted of a low power transmitter, a superregenerative receiver, and a dynamotor for power supply. These 3 units were shock-mounted and housed in a watertight steel box. Connected to this unit was a control box with microphone handset, a battery box containing a 6-volt 170-ampere-hour storage battery, and a special dynamic speaker.

The receiver was of the superregenerative type using a detector tube, an intermediate or "chopper" frequency tube, and an audio amplifier transformer coupled to the detector.

The transmitter used 2 tubes operating as a push-pull unity-coupled oscillator with inductive coupling to the antenna and having a carrier output of approximately 1.5 watts. The modulator section consisted of a speech amplifier which excited a class *B* modulator (tubes connected in push-pull fashion, but with grid voltages of such value that the tubes operate only during positive half cycles). The control circuits were so arranged that during the receiving period the plate voltage was removed from the radio frequency portion of the transmitter, and the speech amplifier and modulator operated as an audio amplifier for the receiver. The audio output of the receiver was sufficient to deliver more than 4 watts of audio power to the loud-speaker. Power for both the transmitter and receiver was supplied from a dynamotor having a 200-volt d-c output and operating from a 6 volt storage battery. The total battery drain was approximately 6 amperes.

On the locomotive, the transmitter-receiver case was mounted on the inside of the locomotive cab between the roof and the back partition of the cab overhang. While this location was not as desirable as others, for experimental purposes it allowed adjustments on the equipment while the train was in motion. The location was especially subject to terrific racking and vibration, and in addition was subject to wide variations in ambient temperature. Temperatures from below zero to 140 degrees Fahrenheit were noted during the tests. The control box with microphone handset was mounted on the back partition of the cab and to the rear of the engineer's seat.

Fig. 2. Transmitting equipment on locomotive tender

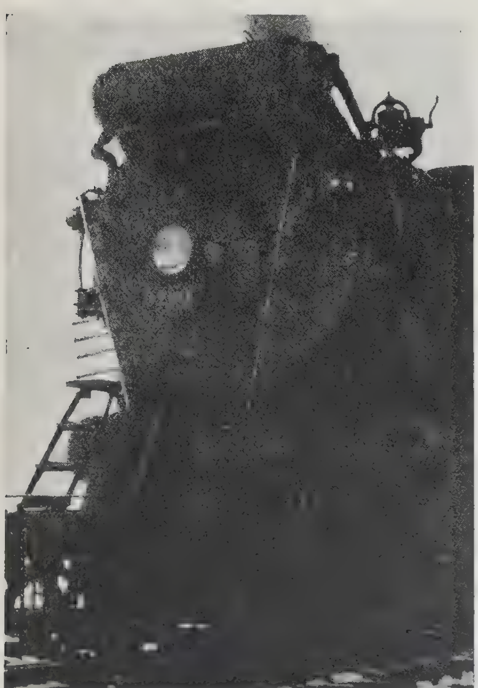


Fig. 1. Half-wave transmitting and receiving antennas mounted on front of locomotive

Because of clearance limitations on the locomotive, it was necessary to mount both the receiving and transmitting antennas on the front of the engine approximately 2 feet from the boiler as shown in figure 1. Each antenna was of the half-wave vertical type. A 2 wire transmission line was run from both the receiver and transmitter to the antennas.

On the caboose, the transmitter-receiver was mounted inside the cupola with the control box so placed that operation could be controlled by a person riding in the cupola. The transmitting and receiving antennas were mounted on each side of the caboose and were of the same type as used on the locomotive.

Additional tests were conducted with a transmitter having an output of approximately 15 watts and operated in conjunction with an 8 tube superheterodyne receiver. The 15 watt transmitter consisted of 2 tubes operating in a push-pull oscillator circuit. A speech amplifier, supplying power to 2 tubes operating as a class *B* modulator, was used in conjunction with the oscillator. The oscillator unit was mounted in a weatherproof metal box. The power supply and modulator were assembled as a separate unit. Power was obtained from a 12–500 volt dynamotor which supplied both the modulator and oscillator unit.

The receiving equipment consisted of an 8 tube superheterodyne with full automatic volume control. Power supply for this unit was obtained from a 6–200 volt dynamotor.

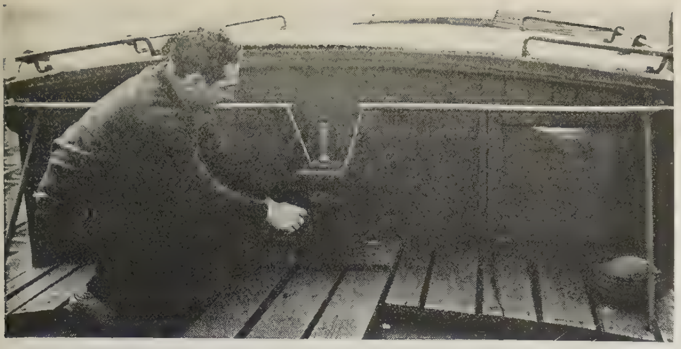


Fig. 3. Transmitter and antenna on cupola of caboose

The general location of this equipment was essentially the same as previously described, except that the transmitter on the locomotive was mounted on the rear deck of the locomotive tender, just back of the coal compartment. The antenna used was of the half-wave horizontal type and was placed adjacent to the transmitter as shown in figure 2.

On the caboose, the transmitter was mounted in the rear of the cupola with a horizontal antenna directly above it as shown in figure 3. The modulator and power supply unit for the oscillator was located in one of the locker spaces in the caboose. In both the locomotive and caboose, the superheterodyne receiver was inclosed in the same case as was used previously for the low power equipment.

Results

In solving the problems listed in the first part of this paper, it should be emphasized that they were viewed from the standpoint of practical reliable communication under actual railroad operating conditions. The tests were made under all kinds of weather conditions, from subzero cold, snow, and ice, to summer heat, rain, and fog. Conclusions were drawn only after several test runs with trains of various lengths had verified the results. The wide range of operating conditions in railway service makes single tests of little value.

Receiver Sensitivity. The receiver sensitivity necessary for satisfactory communication was determined largely by the clearance space available on the locomotive and caboose for the antenna and the permissible background noise level. The sensitivity of both the superregenerative and superheterodyne receivers used was of the order of 5 microvolts per meter for full output. Variations in receiver output were minimized by the use of automatic volume control. The sources of radio interference causing a high noise level were found to be:

1. Automobile and truck ignition systems, especially in cities and near railway stations.
2. Industrial plants close to the right of way.
3. Snow and steam static.
4. The variable contact between metallic parts of the locomotive, caboose, and adjacent cars.

Where the railway was electrified with overhead trolley systems, leakage of the insulators in wet weather added some noise; but passing electric locomotives caused no interference. Altogether a receiver sensitivity of 5 microvolts per meter and an audio output of from 3 to 5 watts proved sufficient. A higher sensitivity was undesirable because of the excess background noise received when the distant transmitter was not in use. Other noticeable effects of mobile operation were in general that when either the locomotive or caboose was passing over or under a bridge with a metal framework overhead, a marked increase in field strength was observed, and when passing through cuts or past buildings a general reduction in field strength was noted.

Transmitter Power. The transmitter power was determined by the requirements for reliable communication with trains up to 200 cars in length and the restrictions imposed by available clearances for antennas on locomotive and caboose. Figure 4 shows the "per cent communication" for the 1.5 watt and 15 watt transmitters for various lengths of trains both stationary and in motion. By "per cent communication" is meant the percentage of transmitted test signals received correctly at the opposite end of the train. The "per cent *intelligible* communication" in actual use would be somewhat higher, because even under conditions when scattered symbols or words are unintelligible most messages still would be received understandably. Data were obtained from actual trials for train lengths up to 130 cars, but were estimated for longer trains. The difference in communication obtained when the train is under way and when it is standing still is attributable partly to the much higher noise level when the train is running and, also, to the variable attenuation of the signal under the running conditions. Figure 5 shows the communication changes at different points along the route. These 2 curves give an over-all picture of mobile communication that is difficult to convey in words. It may be noted that under favorable conditions and with relatively short trains the lower power transmitter gave satisfactory communication for upward of 90 per cent of the time, but with longer trains and at unfavorable points along the route the received signal was rela-

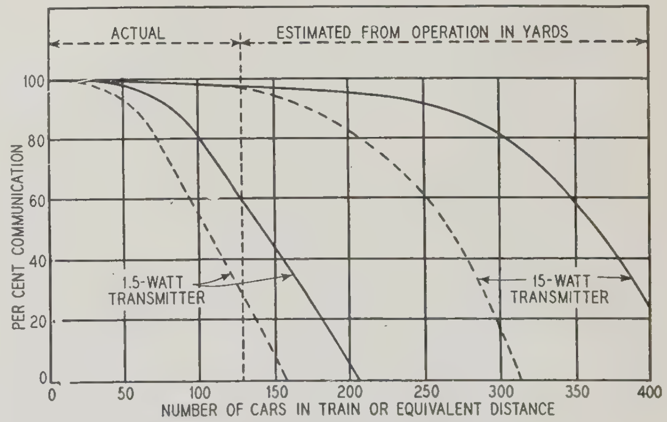


Fig 4. Relative communication efficiency versus train length

Solid line curves are for train standing still; dashed line curves for train running

tively poor, because of long fading periods. During a fading period, the automatic volume control in the receiver attempts to hold the output constant, increasing the sensitivity and hence the background noise which interferes with communication. Higher transmitter power reduced the fading and hence the background noise. From the extensive tests conducted on trains up to 130 cars in length it is believed that under the operating conditions encountered 15 to 25 watts of transmitter power is essential for 200 car trains to assure sufficiently reliable communication.

Carrier Frequency

Tests were made with carrier frequencies in the 60 megacycle, as well as in the 30 to 40 megacycle bands. In general, there was little choice between these frequencies. There was slightly less ignition and industrial interference at 60 megacycles, and the antenna systems required were of smaller dimensions for the same efficiency. Offsetting these effects, the fading and reflections were more marked at 60 megacycles, resulting in somewhat greater variations in received signals. Therefore, the transmitter and receiver frequency stability had to be relatively better at the higher frequencies to give the same reliability of communication. At the present state of the art, it is believed that the 30 to 40 megacycle band is better suited to railroad communication than the 60 megacycle band.

Antenna

Quarter-wave and half-wave antennas of dimensions suitable for 35 and 60 megacycle operation were tested in various locations on the locomotive and caboose. Where clearance limitations permitted, the vertical half-wave antenna was satisfactory. Figure 1 shows the vertical 60 megacycle half-wave antenna on the locomotive. However, in the tests at 35 megacycles the half-wave antenna had to be mounted horizontally. This gave better results than a vertical quarter-wave antenna at the same

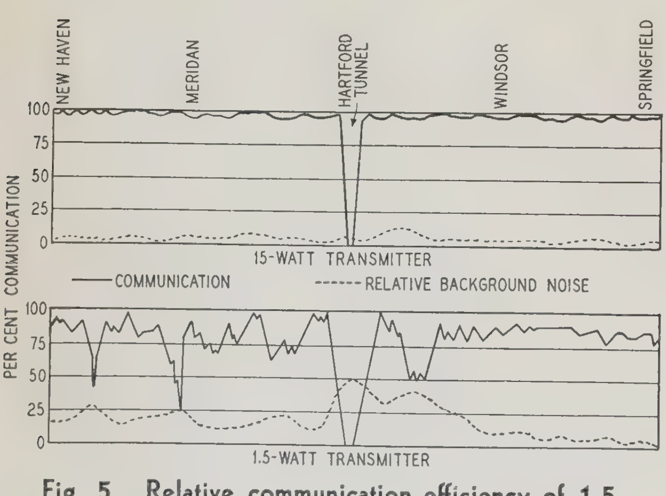


Fig. 5. Relative communication efficiency of 1.5 and 15 watt transmitters on a typical run with an average train length of 60 cars

frequency. Figures 2 and 3 show the 35 megacycle horizontal antenna on the locomotive and caboose. In general, the design and location of the transmitting antenna seemed to affect communication to a greater extent than that of the receiving antenna. It was concluded that for 30 to 40 megacycles, either the half-wave horizontal or half-wave vertical antenna was satisfactory for both transmitter and receiver.

Operating Arrangement

Two general systems of operation may be used: (1) simplex, in which the speaker, by means of a push button on the microphone or otherwise, places his transmitter on the air while speaking; (2) duplex, in which both transmitters are on the air simultaneously during the communication period. In both systems, the receivers are in operation continuously.

Fig. 6. Commercial assembly developed, showing at the left the transmitter and at the right the rectifier

For simplex operation, only one frequency is necessary for both ends of the train, as only one transmitter is on the air at one time. Duplex operation may be slightly faster in that the front to rear and rear to front channels are entirely separate and can be used simultaneously; but this system requires 2 frequencies, one for the locomotive transmitter and one for the caboose transmitter. With the use of the duplex system, there was some interference to the local receiver which resulted in a higher noise level. This apparently was caused by shock excitation of conductors by the local transmitter and variable contacts and sparks between surrounding metal parts. This includes rail and wheel contact, brake rigging, and other metal parts of the locomotive, caboose, and adjacent cars. The results of the tests, during which the train crews operated the equipment at various times, indicated that simplex operation is adequate for this application and is preferred from a practical standpoint because of interference difficulties with the duplex system.

Special Requirements, and Commercial Apparatus Developed

For satisfactory railroad mobile radio communication service, the equipment must be designed to withstand extremely severe shocks, which are common during switching and yard operation. The equipment must be housed in weatherproof boxes but at the same time must be readily accessible for inspection and service.

Making use of the data and experience obtained during the development and test work described, commercial railroad communication equipment was designed. A brief description of this equipment is given in the following paragraphs. Figure 7 shows the arrangement and connection of units for either locomotive or caboose.

Transmitter Assembly. The transmitter is of the master oscillator power amplifier type with an output of 25 watts to the antenna. For both the class *B* modulator and the radio frequency portion of the set type 801 tubes are used, and for the speech amplifier a type 59 tube. A frequency range of from 30 to 42 megacycles is obtainable. In the same case with the radio and audio apparatus is the necessary rectifier for operating the transmitter from the 110-volt 60-cycle a-c supply obtained from the converter. Both rectifier and transmitter are shock-mounted inside the weatherproof steel box. A complete transmitter and rectifier assembly is shown in figure 6. The complete unit requires a total of 250 watts during the transmitting period, and 8 watts during stand-by periods.

Receiver. The receiver is a complete self-contained a-c operated superheterodyne using the same power supply as the transmitter. A sensitivity of better than 5 microvolts per meter, with a minimum of background noise, is obtainable. Full automatic volume control and an undistorted power output of 4 watts are provided. The unit is shock-mounted and housed in a steel weatherproof case. A power input of 50 watts is required. Operating in conjunction with the receiver is a dynamic loud-speaker protected against dust and spray.

Antennas. The transmitting and receiving antennas are of the half-wave horizontal type, shown in figure 7, and consist of $^3/_4$ inch brass pipe approximately 10 feet long with suitable terminations to match a concentric transmission line.

Control Box. A control box is provided which contains a master switch and a telephone handset. The output of the receiver in addition to supplying the loud-speaker operates the ear receiver in the handset so that operation is similar to that of the ordinary telephone. Provision is made so that the complete equipment can be locked when not in use.

Power Supply. When used on engine or caboose, the equipment operates in conjunction with a converter designed to convert the standard 32-volt d-c train supply to 110-volt 60-cycle alternating current which is necessary for operation of the transmitting and receiving equipment. On the engine, power is obtained through the converter directly from the headlight generator which is capable of being operated at all times while the engine is in service.

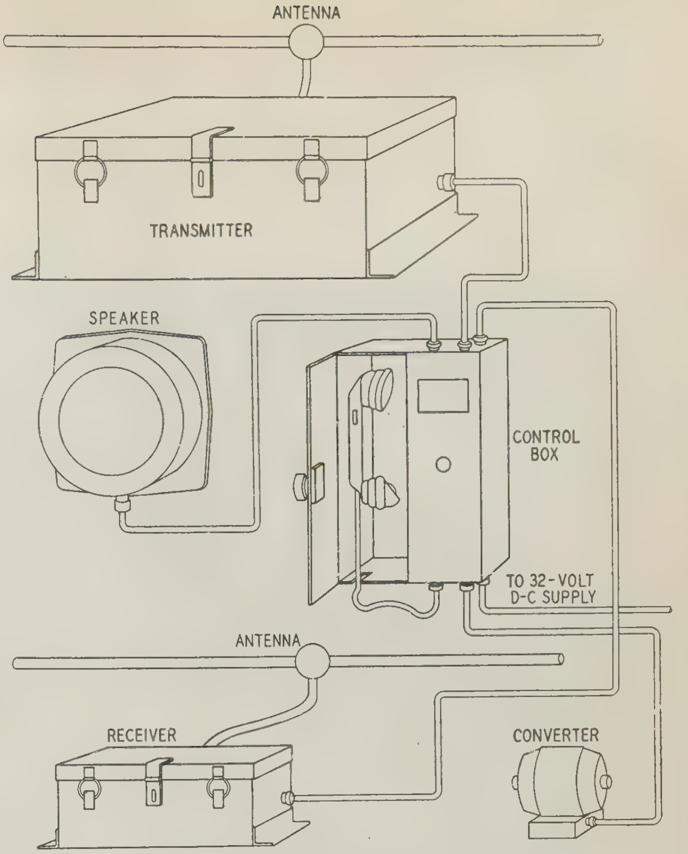


Fig. 7. Schematic diagram showing connections of commercial equipment developed. Equipment for locomotive cab and caboose is identical

In the caboose, it is necessary to install some form of power supply. Many forms, such as an air engine, a gasoline engine, etc., have been considered, but it is expected that the final decision will favor the installation of a 32 volt battery of the standard car lighting type with a small axle driven charging generator.

Installation and Operation. During the receiving period, a current of 5 amperes is required from the 32 volt supply. During the transmitting period, a current of 14 amperes is required.

As both the transmitter and receiver are in weatherproof cases, they may be mounted in any convenient location on the locomotive or caboose.

The control box, and the loud-speaker, receiver, and transmitter cases, together with the necessary wiring, are located as a permanent installation on the locomotive and caboose. The transmitter and receiving units are readily removable from their cases. They may be removed and used for other trains in the event that the engine or caboose is transferred temporarily from a run where radio service normally is employed to a run where the service has not been established.

It is believed that the equipment just described, utilizing the data and experience gained by 18 months of development under actual operating conditions, will provide a communication system meeting the severe requirements of railroad service.

News
Of Institute and Related Activities

Looking north toward Central Park and upper Manhattan from the Rockefeller Center observation roof on top of the 70 story RCA Building in New York City. The festoons of lights at the upper left are on the George Washington Bridge across the Hudson River, and the heavy stream of lights at the right marks Fifth Avenue. The large building to the left of the small oval-shaped area which may be seen at the lower end of Fifth Avenue is the Plaza Hotel between 58th and 59th Streets, where the Institute's dinner dance will be held during the winter convention. North of 59th Street, Central Park extends to 110th Street

A.I.E.E. Winter Convention Affords Technical and Social Opportunities

MANY technical developments and attractive social features are on the program for the A.I.E.E. winter convention which will be held in the Engineering Societies Building, 33 West 39th Street, New York, N. Y., January 28–31, 1936. At the opening of the convention on Tuesday morning recognition will be made to Dr. A. E. Kennelly for having received the triennial Mascart Medal award, mention of which is made elsewhere in this issue. The first of the technical sessions will be held immediately after the opening session, and will continue during the mornings and afternoons of the first 3 days. In the evenings the Edison Medal presentation and lecture, a smoker, and the annual dinner dance will take place. The period of the convention will be interspersed with important committee meetings, conferences, and inspection trips to places of interest where may be seen many diversified uses of electricity. As in the past, Friday will be devoted exclusively to trips. In addition to the other social features of the program Mrs. A. F. Dixon, chairman of the womens' entertainment committee, is arranging an interesting program for the women.

A summarized schedule of events is given in the accompanying tabulation. Plan now to attend the 1936 winter convention and take part in these functions arranged by your committees.

Edison Medal Presentation and Lecture

Dr. Lewis B. Stillwell will be presented with the Institute's Edison Medal for 1935 in the engineering auditorium on the evening of January 29 at 8:15 p.m. The Edison Medal committee awarded the medal to Doctor Stillwell "for distinguished engineering achievements and his pioneer work in the generation, distribution, and utilization of electric energy." Further details on the award and the career of Doctor Stillwell are given on page 122 of this issue.

After the medal presentation a lecture on astronomy will be given by the well-known astronomer, Dr. Harlow Shapley of the Harvard University observatory.

Technical Program

The technical program has been arranged to provide the membership with the latest developments in a number of specialized fields. Thirteen technical sessions in almost as many different fields of activity have been scheduled on the program. The tentative list of papers for these sessions was published in ELECTRICAL ENGINEERING for December 1935, page 1409. With each title is a reference to the issue in which the complete paper is published. The tentative technical program as announced therein is final with the following additions and change.

In the first session on electrophysics, scheduled for Tuesday, January 28, 10:30

a.m., a demonstration, "High Speed Pictures of Mercury Arc Spots" will be given by H. W. Lord of the General Electric Company. In the session on synchronous and other machines scheduled for Wednesday, January 29, 10:00 a.m., in place of the paper on "Mechanical and Electrical Problems Involved in the Design and Construction of Large Turbine Generators" the following paper will be presented:

Sliding Contacts—Electrical Characteristics, R. M. Baker, Westinghouse Electric and Manufacturing Company.
Published in this issue, p. 94–100.

To the session on Transportation the following paper has been added:

Locomotive to Caboose Radio Communication, S. G. Ellis, Westinghouse Electric and Manufacturing Company.
Published in this issue, p. 109–13.

In addition to the 13 sessions at which papers will be presented, another session will be devoted exclusively to electric welding demonstrations. The application of high speed photography to the study of weld phenomena will be demonstrated by H. A. Winne of the General Electric Company. Another interesting demonstration now being worked up by W. E. Crawford of the A. O. Smith Corporation probably will show the phenomena of the flash welding arc. There is also the possibility of another very interesting demonstration, by engineers of the Westinghouse Electric and Manufacturing Company, which, by means of the cathode ray oscilloscope, will show the accuracy of control of an igniter type of rectifier tube in dealing out anything from $^1/_2$ cycle up to any desired number of cycles in each individual weld.

Several round table discussions also will be held on the subject of transformers for communication purposes, network synthesis, and sound; H. S. Osborne, E. L. Bowles, and P. L. Alger, respectively, will preside over these sessions. The discussions at these meetings will not be published but engineers are invited to attend and feel free to take part in the discussions. Notice of the meeting room locations will be posted on the bulletin board during the convention.

Smoker at Mecca Temple

This year the winter convention smoker will be held at Mecca Temple Casino, 133 West 55th Street, New York, N. Y., Tuesday, January 28. It will afford a splendid opportunity for members and their friends to get together for a visit and enjoy an excellent dinner and a full evening of entertainment. Dinner will begin promptly at 6:30 p.m. The committee has arranged for a unique program of entertainment which will be given on the stage in the same hall where dinner will be served. Mecca Temple has been redecorated and modernized and its facilities will meet all of the demands, including plenty of space to gather and talk.

The price of tickets this year will be $2.50 per person, including taxes. All seats will be reserved. Each table will seat 10 persons; parties may be arranged but reservations must be grouped on one application, otherwise seating will be made by the committee.

A large attendance is expected this year and the number of tickets sold will be limited. Therefore, it is advisable to mail your request for tickets and seating with remittance as early as possible to A.I.E.E. Smoker Committee, 33 West 39th Street, New York, N. Y.

Annual Dinner Dance and Buffet Supper

For those who would enjoy meeting their friends in the splendid surroundings of a great metropolitan hotel, the dinner dance has this year been arranged to be held at The Plaza, Fifth Avenue between 58th Street and 59th Street, New York City. A combination dinner, dance, and buffet supper again will be featured.

Because of the flexibility of this arrangement which has been so popular, a pleasant evening may be enjoyed by all according to their tastes, in a hotel which many will remember as one of New York's best.

It may, perhaps, be sufficient to say that the grand ballroom and adjacent facilities, including lounge rooms, will be reserved for the Institute's members and their guests. The Plaza can be counted upon to furnish a menu in keeping with its reputation. Music will be furnished by George Ellner's Orchestra, whose good rhythms may be remembered by many from other enjoyable affairs of the Institute. The arrangement of dances and encores will be that which has been found so successful of late at our annual dances.

The program is:

7:30 p.m.	Dinner
9:30 p.m. to 2:00 a.m.	Dancing
Midnight to 2:00 a.m.	Buffet Supper

The tariffs will be the same as last year:

Dinner and dance	$5.00 per person
Dinner, dance, and buffet supper	$6.50 per person
Dance and buffet supper	$3.00 per person

In order to assist the committee, early purchase of tickets is requested. Dinner reservation requests should indicate names of guests and desired seating arrangements. Tables will be laid for 8 or 10 places and every effort will be made to comply with requests of members.

Reservation requests should be sent to the A.I.E.E. Dinner Dance Committee, 33 West 39th Street, New York, N. Y., checks being made payable to H. H. Henline, national secretary.

Summarized Schedule of Principal Events

Tuesday, January 28

9:00 a.m.	Registration
10:00 a.m.	Opening of convention
10:30 a.m.	Parallel technical sessions: —Communication —Electrophysics—I
2:00 p.m.	Parallel technical sessions: —Instruments and measurements —Electrophysics—II
6:30 p.m.	Smoker at Mecca Temple

Wednesday, January 29

10:00 a.m.	Parallel technical sessions: —Power transmission —Synchronous machines —Electrochemistry and electrometallurgy
12:30 p.m.	Luncheon conference—Student Branch counselors and committee on education
2:00 p.m.	Parallel technical sessions: —Symposium on magnetic materials —Electrical machinery —Automatic stations
8:15 p.m.	Presentation of Edison Medal to Dr. L. B. Stillwell Lecture on astronomy, by Dr. Harlow Shapley

Thursday, January 30

10:00 a.m.	Parallel technical sessions: —Symposium on modernization of distribution systems —Transportation
2:00 p.m.	Parallel technical sessions: —Protective devices —Electric welding demonstrations
7:30 p.m.	Annual dinner dance and buffet supper dance at the Plaza Hotel

Friday, January 31

All Day	Inspection trips

Inspection Trips

Preliminary arrangements made by the inspection trips committee reveal many attractive features. Seventeen visits have been planned covering a wide variety of subjects—some highly technical, others of general engineering interest, and still others chosen more for their broad educational value than for their close relation to electrical engineering.

As in past years, Friday will be devoted exclusively to inspection trips, but visits have been planned for the other days of the convention in such a way as to supplement the technical sessions on those days.

The schedule, which is subject to change, follows:

Tuesday, January 28

1. RCA Radiotron Company
2. New York Police Department—ballistics bureau and radio communication

Wednesday, January 29

1. Hell Gate generating station—automatic frequency and load control
2. Electric Fireboat "John J. Harvey"
3. General Cable Corporation
4. Hayden Planetarium

Thursday, January 30

1. Metropolitan Device Corporation
2. Electrical Research Products, Inc.
3. Columbia Presbyterian Medical Center
4. The New York Edison Company, Inc.—splicing school

Friday, January 31

1. Bell Telephone Laboratories
2. Radio City Music Hall
3. New York Stock Exchange
4. Pyrene Manufacturing Company—fire fighting demonstration
5. "Monarch of Bermuda"
6. General Electric "House of Magic"
7. National Broadcasting Company studios

One of the most interesting features having general appeal is a visit to the Hayden Planetarium where a special program has been arranged, including a lecture by Dr. Clyde Fisher, curator of the department of astronomy of the American Museum of Natural History.

Of unusual interest to members will be an inspection trip to the physiological laboratories of the Columbia Presbyterian Medical Center where the application of electricity and electrical measurements to physiology may be seen.

Several motor bus trips have been ar-

ranged without charge to members through the courtesy of co-operating companies. These include a demonstration of fire fighting by the Pyrene Manufacturing Company in Newark, N. J., a visit to the Bayonne plant of the General Cable Corporation, and a trip to Hell Gate generating station of the New York Edison Company, Inc., where automatic frequency and load control apparatus and 132 kv cable terminals may be seen.

Interesting electric welding operations will be seen at the plant of the Metropolitan Device Corporation, as well as a novel method of electric baking recently developed by that company.

The visits on the regular schedule have been carefully selected with a view to meeting the desires of the largest number of members. The committee conceives it to be its duty and pleasure to make it possible for any member attending the convention to inspect the things in which he is most interested. To this end special trips will be undertaken, in so far as practicable, for small groups who make application in time for arrangements to be completed. A list of possible special objectives, including substations, generating stations, laboratories, manufacturing plants, etc., is being compiled and will be made available at the opening of the convention.

Because of possible changes in the regular schedule given above, inquiry should be made at the inspection trips desk at the opening of the convention. It is earnestly requested that members apply promptly for reservations inasmuch as, in several instances, the numbers which can be accommodated are necessarily limited.

Hotel Rates

Reservations for hotel accommodations should be made by writing directly to the hotel of your preference. The Plaza, where the dinner dance will be held has arranged for special room rates during the convention. In table I is included a brief list of some of the leading hotels in the vicinity.

Table I—A Few of the Hotels Available

Hotel	Location	Rooms With Private Bath: Single	Rooms With Private Bath: Double
Astor	Broadway and 44th St.	$3.00– 6.00	$4.00– 8.00
Biltmore	Madison Ave. and 43rd St.	4.00–10.00	7.00–12.00
Commodore	Lexington Ave. and 42nd St.	3.00– 5.00	4.50– 8.00
Edison	228–248 W. 47th St.	2.50– 5.00	4.00– 8.00
Governor Clinton	31st St. and 7th Ave.	3.00– 5.00	4.00– 7.00
McAlpin	Broadway and 34th St.	2.50– 7.00	4.00– 9.00
Murray Hill	Park Ave. and 40th St.	2.50– 5.00	3.50– 7.00
New Yorker	8th Ave. and 34th St.	3.50– 8.00	5.00–10.00
Pennsylvania	7th Ave. and 32nd St.	3.50– 6.00	5.00– 9.00
Plaza	Fifth Ave. and 59th St.	5.00	7.00
Roosevelt	Madison Ave. and 45th St.	4.00– 8.00	6.00–12.00
Vanderbilt	Park Ave. and 34th St.	3.00– 5.00	5.00– 8.00
Waldorf-Astoria	Park Ave. and 50th St.	5.00– 8.00	8.00–12.00

Reduced Railroad Rates

Fare and one-third for the round trip over the same route will be available to members and guests, provided 100 certificates are validated at the registration desk. Consult your local ticket agent regarding the territory and dates applicable. Obtain your certificate authorized by the railroad passenger associations.

Register in Advance

Members in nearby Districts should fill in and post promptly the mail registration card which was included with the mailed announcement of the winter convention sent them. This will permit the committee to have badges ready and prevent congestion at the registration desk upon arrival. There will be a registration fee of $2 for non-members with the exception of Enrolled Students of the Institute, and the immediate families of members.

Columbia Alumni Dinner

A dinner for the electrical engineering alumni of the Columbia University school of engineering will be held on Wednesday, January 29, 6:30 p. m. at the Columbia University Club, 4 West 43d Street. The dinner will conclude in time to permit attendance at the Edison Medal presentation. Dinner reservations at $1.50 may be made with A. D. Hinckley, school of engineering, Columbia University, New York, N. Y.

A.I.E.E. Executive Committee Meets

A meeting of the executive committee of the A.I.E.E. was held at Institute headquarters, New York, N. Y., on December 11, 1935, in place of the regular meeting of the board of directors.

There were present: President E. B. Meyer (chairman), Everett S. Lee, L. W. W. Morrow, W. I. Slichter, R. H. Tapscott, J. B. Whitehead, members of the committee; C. R. Jones, director; H. H. Henline, national secretary.

Resolutions were adopted in memory of Edwin Wilbur Rice, Jr., a past-president and Honorary Member of the Institute, who died on November 25. (The resolutions appear elsewhere in this issue.)

A report of a meeting of the board of examiners held November 13, 1935, was presented and approved. Upon the recommendation of the board of examiners, the following actions were taken: 1 applicant was elected and 2 applicants were transferred to the grade of Fellow; 29 were elected and 32 were transferred to the grade of Member; 104 were elected to the grade of Associate; 854 Students were enrolled.

Expenditures amounting to $21,694.30 in the month of November and $20,878.37 in December were reported by the finance committee and approved.

Chairman Everett S. Lee reported a slight increase over last year in the number of applications for membership received since May 1, and the highest percentage of paid-up members since 1920.

The selection by the District executive committee of the dates of May 6–8 for the previously authorized North Eastern District meeting to be held in New Haven, Conn., in 1936, was reported.

The appointment by the president, upon the recommendation of the standards committee, of A. J. Williams, Jr., as an A.I.E.E. representative on the Sectional Committee on Vacuum Tubes for Industrial Purposes, of the American Standards Association, was reported and approved.

Report was made that the board of di-

Membership—

Mr. Institute Member:

Your loyal participation in sending in names, together with the continuously effective work of the Section membership committees, has brought the number of new applications for membership received since May 1, 1935, to a total of 426 as of December 1, 1935.

In the corresponding period of the previous year, 408 new applications for membership were received.

Your continued helpful participation in sending in names will make for continued advance.

Everett S. Lee

Chairman National Membership Committee

rectors by letter ballot, since its October meeting, had voted to accept an invitation to the Institute to be represented on the American National Committee of the Third World Power Conference, which is to be held in Washington, D. C., September 7–12, 1936.

An invitation was presented from the department of mechanical engineering of Lehigh University for the Institute, particularly its members in the Lehigh Valley, Pa., to participate in the celebration at the university, on January 20, of the 200th anniversary of the birth of James Watt. It was voted that a notice of this event should be published in the January issue of ELECTRICAL ENGINEERING.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Louisiana Engineering Society to Meet

The Louisiana Engineering Society is amplifying its annual meeting for 1936 into a 2 day session to take place on January 24 and 25, with headquarters at the St. Charles Hotel, New Orleans, La.

The program calls for registration Friday morning, January 24, at headquarters of the society, a meeting of district representatives, and a general meeting of the society; and visits to plants and points of interest Friday afternoon.

The technical program will be held Saturday morning, with Saturday afternoon open for recreational activities. The annual banquet at the St. Charles Hotel, Saturday night, will conclude the meeting. Ample opportunity will be provided for members of the society and all other interested engineers to take part in both technical and social events.

The New Orleans Section of the A.I.E.E. is co-operating in this meeting, and will furnish the program for one session.

A.I.E.E. Officers to Be Nominated Soon

The national nominating committee of the A.I.E.E. will meet during the winter convention, New York, N. Y., January 28–31, 1936, for the purpose of nominating national officers to be voted upon by the membership in the spring of 1936. The national nominating committee which has been named in accordance with the By-laws is as follows:

Representing the Board of Directors

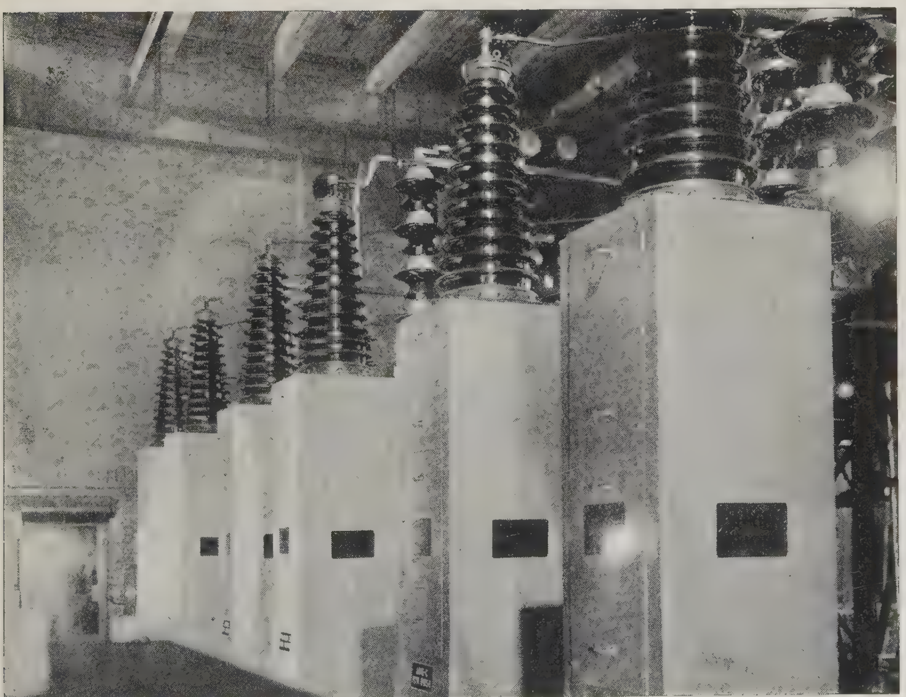
F. M. Farmer   W. B. Kouwenhoven
W. H. Harrison   A. C. Stevens   Everett S. Lee

Representing the Geographical Districts

Dist. 1. W. H. Timbie, Massachusetts Institute of Technology, Cambridge.
Dist. 2. W. E. Wickenden, Case School of Applied Science, Cleveland, Ohio.
Dist. 3. H. R. Woodrow, Brooklyn Edison Company, Brooklyn, N. Y.
Dist. 4. F. M. Craft, Southern Bell Telephone and Telegraph Company, Atlanta, Ga.
Dist. 5. F. H. Lane, Byllesby Engineering and Management Corporation, Chicago, Ill.
Dist. 6. H. S. Evans, University of Colorado, Boulder.
Dist. 7. C. W. Mier, Southwestern Bell Telephone Company, Oklahoma City, Okla.
Dist. 8. O. W. Holden, Bureau of Power and Light, Los Angeles, Calif.
Dist. 9. J. A. Thaler, Montana State College, Bozeman.
Dist. 10. C. V. Christie, McGill University, Montreal, Que., Canada.
L. B. Chubbuck (alternate) Canadian Westinghouse Company, Hamilton, Ont.

The amended provisions of the constitution and by-laws relating to nomination of officers were given in ELECTRICAL ENGINEERING for November 1935, page 1270, wherein members were invited to submit suggestions for nominations not later than December 15, 1935. The methods whereby nominations also may be made independent of the nominating committee were given in that item. Briefly, independent nominations may be made by a petition of 25 or more members sent to the national secretary at Institute headquarters, not later than March 25, to be placed before the nominating committee for inclusion in the ballot of such candidates as are eligible. Petitions for the nomination of vice president may be signed only by members within the District concerned.

132 Kv Cable Terminals at Hell Gate



THE cable terminals on the 132 kv underground feeders at Hell Gate generating station of the New York (N. Y.) Edison Company, may be seen by those attending the Institute's winter convention in New York, January 28–31, 1936.

Future AIEE Meetings

Winter Convention,
New York, N. Y., Jan. 28–31, 1936

North Eastern District Meeting,
New Haven, Conn., May 6–8, 1936

Summer Convention,
Huntington Hotel, Pasadena, Calif., June 22–26, 1936

Middle Eastern District Meeting,
Pittsburgh, Pa., part of week of Oct. 12, 1936

Mascart Medal Awarded to Past-President Kennelly

Announcement has been made that the Société Française des Électriciens has awarded the Mascart Medal for 1936 to Dr. A. E. Kennelly (A'88, F'13, HM'33, Life Member, and past-president) professor emeritus of electrical engineering, Harvard University and Massachusetts Institute of Technology, Cambridge. Recognition of this award to Doctor Kennelly is to be made during the opening session of the A.I.E.E. winter convention in New York, N. Y., Jan. 28–31, 1936. Doctor Kennelly, who has long been active in the affairs of the Institute, having served as president 1898–1900, was chosen by reason of the numerous and eminent works which he has to his credit and the very valuable collaboration which he has given to international electrical congresses and affairs. (Biographical sketches of Doctor Kennelly's career appear in ELECTRICAL ENGINEERING for July 1935, page 798, and in this issue, page 123.)

The Mascart Medal was established by the Société Française des Électriciens in 1923 as a triennial medal to be awarded in honor of Mascart, the eminent scientist who founded that society, the Laboratorie Central, and the École Superieure d'Electricité. According to the terms of the by-laws adopted for this award, the medal will be conferred upon a scientist or an engineer, French or foreign, whether or not he is a member of the society, who is distinguished by a group of works on pure or applied electricity.

The committee of this society, at its meeting of November 20, 1935, decided, by acclamation, to award the medal for 1936 to Doctor Kennelly. The previous awards of the medal have been made to:

1924 Andre Blondel (A'05, HM '12)
1927 Sir J. J. Thomson
1930 Paul Janet
1933 Paul Boucherot

United States National Committee of I.C.I. Meets

The United States national committee of the International Commission on Illumination held its annual meeting at Engineering Societies' Building, New York, N. Y., November 15, 1935. G. H. Stickney was re-elected president and Prof. H. B. Dates was elected secretary-treasurer. Messrs. Stickney and Dates were also chosen as U.S. members of the I.C.I. executive committee.

The committee approved, with only a few minor reservations, all of the resolutions adopted by the I.C.I. meeting in Karlsruhe, Germany, last July. Prof. C. D. Fawcett was reappointed director of the I.C.I. secretariat on lighting education and Prof. H. B. Dates of the secretariat on lighting practice. U.S. representatives were appointed for the new list of I.C.I. technical committees.

Other plans were formulated in preparation for the I.C.I. convention which is scheduled to be held in Holland in 1938. The commission and the U.S. committee are both in prosperous condition and are undertaking significant work of importance in the lighting field.

Among notable recent accomplishments are the assurance of a satisfactory primary standard of light, elimination of discrepancies in photometry, and a guiding outline of practice and regulations for aviation lighting.

Refrigerating Machinery Standards Adopted. A standard entitled "Proposed Standard Method of Rating and Testing Mechanical Condensing Units" has been approved by the American Society of Refrigerating Engineers, the Refrigerating Machinery Association, and the refrigeration division of the National Electrical Manufacturers Association. These standards, consisting of a 14 page $8^1/_2$ by $11^1/_2$ inch pamphlet, are obtainable from the American Society of Refrigerating Engineers, 37 West 39th Street, New York, N. Y., at a cost of 15 cents each. Another standard "Proposed Standard of Rating and Testing Air Conditioning Equipment," mention of which was made in ELECTRICAL ENGINEERING for December 1935, page 1413, also has been approved. The latter standard also may be obtained from the American Society of Refrigerating Engineers. It consists of 19 $8^1/_2$ by $11^1/_2$ pages, and costs 20 cents per copy.

Watt Bicentennial to Be Celebrated

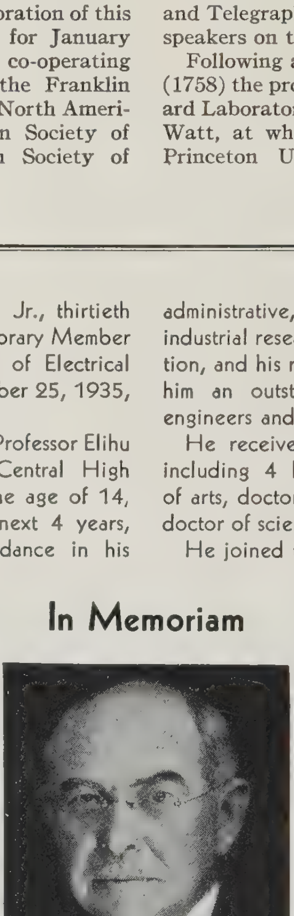
The 200th anniversary of the birth of James Watt occurs on January 19, 1936. Under the initiating auspices of the mechanical engineering department of Lehigh University, Bethlehem, Pa., a celebration of this anniversary is being planned for January 19–21, 1936. Among those co-operating with Lehigh University are the Franklin Institute of Pennsylvania, the North American branch of the Newcomen Society of England, and The American Society of Mechanical Engineers. Ceremonies will be held in Bethlehem and Philadelphia, Pa.

According to the tentative program, the celebration will commence on Sunday, January 19, at the Franklin Institute, Philadelphia, with special displays and demonstrations of models of the steam engines of Newcomen and Watt, and other appropriate exhibits; an international broadcast from the birthplace of Watt will be a feature of this portion of the program.

The morning session, January 20, at Lehigh University, Bethlehem, will take the form of a discussion on "The College Graduate in Industry," which will be held at the Packard Laboratory. Dean R. L. Sackett, Pennsylvania State College, will preside, and Dean R. H. Fernald, University of Pennsylvania, F. M. Feiker, executive secretary of American Engineering Council, and O. W. Eshbach (A'07, M'30), American Telephone and Telegraph Company, will be among the speakers on the program.

Following a luncheon at the Old Sun Inn (1758) the program will be resumed at Packard Laboratory, with a colloquium on James Watt, at which Dean A. M. Greene, Jr., Princeton University, will preside. Ad-

In Memoriam



EDWIN WILBUR RICE, JR.

DR. Edwin Wilbur Rice, Jr., thirtieth president and an Honorary Member of the American Institute of Electrical Engineers, died on November 25, 1935, at the age of 73.

Coming in contact with Professor Elihu Thomson, a teacher in Central High School, Philadelphia, at the age of 14, he received, during the next 4 years, much inspiration and guidance in his favorite subjects, mechanics and electricity, and at the age of 18 became assistant to Professor Thomson who at that time accepted a position in electrical manufacturing with the American Electric Company.

He progressed rapidly in his chosen work, becoming plant superintendent of the Thomson-Houston Electric Company, successor to the American Electric Company, at the age of 22. With the consolidation of 2 companies in 1892 to form the General Electric Company, Mr. Rice became technical director of the latter. Later he served successively as vice president in charge of manufacturing and engineering, senior vice president, president, and honorary chairman of the board of directors.

His contributions, both technical and administrative, to electrical manufacturing, industrial research, invention, and education, and his rare personal qualities won him an outstanding reputation among engineers and industrial leaders.

He received numerous high honors, including 4 honorary degrees: master of arts, doctor of engineering, and 2 of doctor of science.

He joined the Institute in 1887, was transferred to the grade of Member in 1888, and was transferred to the grade of Fellow in 1913. He was president of the Institute 1917–18, and served at various times upon many of its committees. The Edison Medal for 1931 was awarded to him, and he was elected an Honorary Member in 1933.

RESOLVED: That the executive committee of the American Institute of Electrical Engineers, upon behalf of the membership, hereby expresses deep regret at the death of Doctor Rice, and records its high appreciation of his many contributions to Institute development and activities, and be it further

RESOLVED: That these resolutions be entered in the minutes and transmitted to members of his family.

—A.I.E.E. Executive Committee, Dec. 11, 1935

Fireboat "John J. Harvey"

NEW YORK CITY'S electric fireboat "John J. Harvey," shown during the celebration of the arrival of a new steamship in New York Harbor. The "John J. Harvey" is included on the very interesting list of inspection trips scheduled to be held in New York during the Institute's winter convention, January 28–31, 1936.

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dresses will be delivered by G. A. Orrok, Dean Dexter S. Kimball, Cornell University, and J. W. Roe. Opportunity also will be provided for the inspection of a display of books, documents, and working models, relating to early engineering development.

Following an informal dinner at the Hotel Bethlehem, an evening session will be held at Packard Auditorium, at which Dean C. C. Williams of Lehigh University will preside. Addresses will be delivered by W. L. Batt, president, A.S.M.E., and W. C. Dickerman, president, the American Locomotive Company.

On Tuesday, January 21, the ceremonies will be transferred to the Franklin Institute, Philadelphia. The afternoon will be devoted to special displays and exhibits, and to a meeting conducted by the North American Branch of the Newcomen Society, at which L. F. Loree, president, Delaware and Hudson Railway, Andrew Baxter, Jr., president, St. Andrews' Society of the State of New York, Sir Gerald Campbell, British Consul General, New York, and Charles Penrose, vice president for North American Branch of the Newcomen Society, will speak. A formal dinner will be addressed by persons eminent in national engineering and scientific affairs.

The Watt bicentennial committee consists of Fred V. Larkin, director, department of mechanical engineering, Lehigh University; H. B. Allen, director, the Franklin Institute; C. E. Davies, secretary, A.S.M.E.; and Charles Penrose.

Members of the national societies of civil, mining and metallurgical, electrical, and mechanical engineers are invited to attend the various ceremonies.

Student Committee of District No. 2 Meets

The annual conference of counselors and Student Branch chairmen for the Institute's Middle Eastern District (number 2) was held at State College, Pa., October 25 and 26, 1935. The department of electrical engineering of Pennsylvania State College was the host with Prof. L. A. Doggett in charge of arrangements. The meeting was held early in the school year so that the newly elected Branch chairmen might benefit from the conference and thereby better carry on the work. The early date also favored travel by automobile, resulting in a registered attendance of 61. The following is a list of the counselors present and the institution which they represented:

John T. Walther, University of Akron
G. McC. Porter, Carnegie Institute of Technology
A. C. Seletzky, Case School of Applied Science
E. O. Lange, Drexel Institute
A. G. Ennis, George Washington University
J. H. Lampe, Johns Hopkins University
F. W. Smith, Lafayette College
J. L. Beaver, Lehigh University
L. A. Doggett, Pennsylvania State College
H. E. Dyche, University of Pittsburgh
H. S. Bueche, Villanova College
A. H. Forman, West Virginia University

The following Branch chairmen were present:

R. D. Heyburn, University of Akron
P. H. Wyckoff, Carnegie Institute of Technology
R. S. Walleigh, George Washington University
W. E. Bittrick, Johns Hopkins University
J. A. Doremus, Lafayette College
H. C. Bickel, Lehigh University
F. F. Fowler, Ohio Northern University
R. O. Bell, Pennsylvania State College
O. D. Montgomery, University of Pittsburgh
J. J. McBrearty, Villanova College
A. C. Fagerlund, West Virginia University

The conference started with registration on Friday afternoon. At 7 o'clock a dinner meeting was held with W. E. Leonhard, Penn State '36, as toastmaster. The principal speakers were W. H. Harrison, the vice president for District number 2 and A. O. Morse, assistant to the president of Pennsylvania State College. Mr. Morse welcomed the counselors and Students and gave an inspiring address advising the Students as to what they should get out of their college career. Mr. Harrison showed in a convincing manner why electrical engineering students should enroll in the Student Branches. He pointed out that the Branches were not intended to serve as feeders to the Institute, but that they provided the students a means whereby they gradually attained the status of active members in the Institute, without any abrupt adjustment on their part. Other speakers were Prof. C. L. Kensloe, head, department of electrical engineering, Pennsylvania State College; Prof. A. H. Forman, West Virginia University; and R. O. Bell, Student Branch chairman at Pennsylvania State College.

At a joint meeting of counselors and students on Saturday morning, interesting and instructive papers were presented on the subject, "A Résumé of Recent Electrical Engineering Graduate Theses at My Institution" by the following students:

T. B. Jones, Johns Hopkins University
J. J. McBrearty, Villanova College
A. C. Fagerlund, West Virginia University
J. R. Parker, Case School of Applied Science
H. C. Bickel, Lehigh University
C. M. Kearns, Pennsylvania State College

This joint conference was adjourned for a short recess, after which the Students met and discussed their problems and exchanged ideas on how to best operate their Branches.

The counselors met at Professor Doggett's home where each counselor present reported on the activities of his Branch. A nominating committee reported the name of Prof. E. O. Lange of Drexel Institute, and on motion he was unanimously elected chairman, committee on student activities of District number 2 for the next year.

At 12:30 the counselors and Students assembled for lunch. The program for the afternoon included an inspection tour through the electrical engineering laboratories, after which many accepted an invitation to be guests at either the Penn State and Lafayette soccer game or the football game between the Penn State freshmen and Wyoming Seminary.

50th Anniversary of First A-C System in America

March 20, 1936, will mark the 50th anniversary of the memorable March 20, 1886, when, at Great Barrington, Mass., William Stanley placed in successful operation his experimental alternating current electric power distributing system, thus demonstrating the commercial feasibility of the a-c system.

As previously announced, the A.I.E.E. board of directors adopted a resolution on August 6, 1935, to the effect that the Institute sponsor a suitable national celebration of this 50th anniversary of the a-c system, and that a national committee be appointed by the president to initiate and carry out this proposal. The committee which now has been appointed is as follows:

A. W. Berresford, chairman, New York, N. Y.
H. H. Barnes, Jr., New York, N. Y.
J. T. Barron, Newark, N. J.
H. P. Charlesworth, New York, N. Y.
C. C. Chesney, Pittsfield, Mass.
F. M. Farmer, New York, N. Y.
W. J. Foster, Schenectady, N. Y.
N. E. Funk, Philadelphia, Pa.
H. B. Gear, Chicago, Ill.
Sidney Hosmer, Boston, Mass.
D. C. Jackson, Cambridge, Mass.
S. M. Kintner, East Pittsburgh, Pa.
V. M. Montsinger, Pittsfield, Mass.
L. W. W. Morrow, New York, N. Y.
Charles F. Scott, New Haven, Conn.
F. W. Smith, New York, N. Y.
C. E. Stephens, New York, N. Y.
J. B. Whitehead, Baltimore, Md.

Among plans which are now in progress is one making possible the participation by all the Sections of the Institute, through Section meetings to be held on or about March 20. A total of 31 Institute Sections had, by December 23, 1936, already signified their intention of holding celebration meetings for this event.

Activities now being carried on by the committee give assurance that the occasion will have national significance and interest.

Lightning Reference Book Canvass Continued

As the result of notices published in ELECTRICAL ENGINEERING (Aug., p. 907; Sept., p. 918, 1008) concerning the lightning and insulator subcommittee's proposal to compile and publish a "Lightning Reference Book" embracing articles published in technical periodicals during recent years, about 200 inquiries have been received to date from members who have indicated a desire to purchase the book if and when issued. However, the price ($5) previously announced by the subcommittee was based upon a larger edition. Consequently, the subcommittee is now making a subscription drive.

Whether or not the contemplated book will be published is now scheduled to be decided by the subcommittee subsequent to Feb. 1, 1936, the date now set by it for final returns from the canvass now under way. Inasmuch as the publication of the book would involve considerable expense, and as the subcommittee plans to operate on a no-profit basis, sufficient interest and adequate financial support (as indicated by advance orders received by Feb. 1) must be pledged in advance.

Further information on this subject will be published in these columns when it becomes available.

Executive Committee of Southern District Meets

A meeting of the executive committee of the Institute's Southern District (number 4) was held at Atlanta, Ga., on November 2, 1935, with the following present:

R. Cooper Bailey, Richmond, Va.
W. Hand Browne, Jr., Raleigh, N. C.
S. C. Commander, Memphis, Tenn.
M. Eldredge, Memphis, Tenn.
R. F. Crenshaw, Memphis, Tenn.
F. E. Johnson, New Orleans, La.
Sam R. Rhodes, Clemson College, S. C.
J. G. Tarboux, Knoxville, Tenn.
Chase Hutchinson, Knoxville, Tenn.
J. H. Perkins, Birmingham, Ala.
E. F. Smith, Gainesville, Fla.
Geo. M. Miller, Louisville, Ky.
J. H. Persons, Atlanta, Ga.
F. M. Craft, Atlanta, Ga.
S. A. Flemister, Atlanta, Ga.

The first subject discussed was the selection of a co-ordinating committee, according to section 33 of the by-laws. Since there is such a small number of Sections in the Southern District, it was suggested that the executive committee act as a co-ordinating committee, and a motion to that effect was made and approved.

The questions of holding a Student conference and of holding a District meeting during 1936 were discussed. It was tentatively planned to hold a joint District meeting and Student Branch conference in the late fall of 1936.

The next subject considered was the selection of a delegate to serve as a member of the national nominating committee, F. M. Craft being chosen for this position.

Methods of increasing membership in the Institute were next considered. The advantage was pointed out of planning the activities of the Section, including speakers and entertainment, well in advance, in order that prospective members might obtain a clearer idea of the facilities being provided by membership. Plans of other Sections in obtaining members and in having individuals transfer from local membership to national membership were given. The necessity of using quality rather than quantity as a guide in seeking new members if the Institute is to retain its high position, was stressed. It was also pointed out that most members in the Southern District are more interested in operating problems and applications of electrical machinery, than in the more frequently considered subjects of design, research, and theoretical problems, often involving intricate mathematics.

Consideration was given to the matter of a new Section in Knoxville and East Tennesse, and Prof. J. G. Tarboux and Chase Hutchinson were requested to continue the work of organization.

The last subject discussed was the co-ordinating of the time of Section meetings so as to take advantage of the opportunities to hear engineers from the large manufacturers and from headquarters, or others who might be available. Methods of co-ordinating through the District secretary were worked out.

Following adjournment, the delegates became guests of the Atlanta Section at luncheon, after which many attended the football game between Vanderbilt University and Georgia Institute of Technology.

E.C.P.D Considers Guide for Student Selection

If a boy is proficient in mathematics in high or preparatory school is he likely to make a success of an engineering course in college? Suppose he is good in spelling, or has a good vocabulary, or can write a good letter or report, do those accomplishments have any bearing on the question of whether or not he should take up engineering? These are some of the things that the committee on student selection and guidance, of the Engineers' Council for Professional Development, is working out.

Preliminary results indicate that the answer to the first question is "yes," which is not entirely surprising. A year ago 8 well-known engineering schools, at the committee's request, gave to their incoming freshmen the co-operative test in mathematics as developed by the American Council on Education. At the end of the year the rating of each student in this test was compared with his general scholastic average for the year, and a so-called correlation determined. If this coefficient were as high as 1 it would mean that the test was a perfect indication of what the student would accomplish during the year; if the coefficient were 0 it would mean that the test had no bearing whatever on what he would do in his first year at an engineering college. The general average for 1,767 students turned out to be 0.55, indicating that the mathematics test was an excellent indication of freshman accomplishments. Other tests have shown that the correlation between the first year and the other 3 years of a 4 year course is high. If a freshman fails in but 1 subject he has a good chance to graduate in the regulation 4 years, but if he has more than 1 failure his chance is slim without summer school, tutoring, or correspondence courses.

Entering freshmen at the same 8 engineering colleges also were given a special test in English, which was in 3 parts covering spelling, vocabulary, and usage. The resulting correlation between the English test score and the first year average for all subjects in the engineering curriculum was about 0.40, or lower than for the mathematics test, but still indicative that a student proficient in the various branches of English is adaptable to engineering work. A less comprehensive study at one engineering college alone, showed that usage ranked far above vocabulary and spelling as an indicator of engineering aptitude. That is, one may be poor in spelling and still be likely to succeed as an engineering student, but ability in the *use* of English is about as necessary as to be proficient in mathematics. In other words, an engineer must be able to organize and express his thoughts in clear, concise English.

The committee directed similar work at a larger number of engineering schools in September of this year, and the correlations begun last year will be continued throughout the entire engineering course. Other tests of engineering aptitude also are being developed. It has been found that ability in descriptive geometry is an especially good criterion of the probable success of a student in engineering curricula, and it is hoped that a test can be devised for potential engineering students that will measure the same quality of imagination that descriptive geometry does. At present, there is no thought that these tests will be used to exclude students from engineering schools, but the committee is seeking tests that will aid in selecting better students and in assuring them that they have interests and aptitudes that are likely to assure their success in the engineering field. Dean R. L. Sackett, of the school of engineering at the Pennsylvania State College, as chairman of the committee, is directing the work.

Another important phase of the committee's activities is the organization of guidance programs and procedures for the aid of preparatory school students. Many of the local branches of the national engineering societies that are sponsoring the Engineers' Council for Professional Development have appointed committees to address high school groups and to confer

with individual students about interests, aptitudes, curricula, and fields of work. Professional engineers are especially active in this work in Milwaukee, Birmingham, Schenectady, Cleveland, Detroit, Atlanta, Kansas City, Sacramento, Baltimore, St. Louis, Providence, Philadelphia, and Washington. These engineers supplement the work of the vocational advisers at many schools. Wide distribution of a pamphlet "Engineering: A Career—A Culture" has been a valuable aid. This may be obtained for 15 cents from Engineers' Council for Professional Development, 29 West 39th Street, New York, N. Y.

Though only 1 of the 4 major activities of the Engineers' Council for Professional Development, student selection and guidance is fundamentally of great importance for it seeks to awaken an interest in engineering in those young men—and an occasional girl as well—that are likely to achieve the highest success in the engineering field. If only the right men are encouraged to enter engineering schools a long step will have been taken toward increasing the recognition accorded to the profession.

American Engineering Council

Second Report of the Science Advisory Board

As part of its "news letter" of December 15, 1935, American Engineering Council offers the following comments on the recent report of the Science Advisory Board covering the period of September 1, 1934, to August 31, 1935.

The second report of the Science Advisory Board, established by executive order of President Roosevelt in July 1933, under the National Research Council created by Congress at the request of President Wilson in 1918, has just been published. Like the National Resources Committee, it addresses itself to certain problems of national development in which the engineer and scientist have a part.

The Science Advisory Board has no authority for action. It may only recommend. Both reports attempt to give broad direction to national policies—the one emphasizing the values of a planned approach to national development, the second concerning itself with the relating of government to effective research and what may be called the "tools" of planning.

The general report of the Science Advisory Board covers such subjects as the national dependence on science, the need for a science advisory service to government, and the future development of a science advisory service. It recommends, first, that a body be set up under the National Academy of Sciences, to succeed the present reporting board, and second, that the responsible government officers and this new board continue to seek the solution of the problems which have been reported upon.

The second part of the report deals with the reorganization and reconsideration of certain of the scientific branches of the government, including the weather bureau, the bureau of chemistry and soils, the surveying and mapping services of the federa government, the relation of patents to new industries, and a dozen other reports of inquiries into the purposes and the efficiency of present government undertakings.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Neutralizing Transformers for Pilot Wire Protection

To the Editor:

The writer has read with special interest, the paper on "Pilot Relay Protection," by E. E. George and W. R. Brownlee in the November 1935 issue of ELECTRICAL ENGINEERING, pages 1262–9. He has been in communication with the authors and pointed out to them that theirs is not the first application of neutralizing transformers to pilot wire protection, submitting the following references:

The discussion at A.I.E.E. midwinter convention at New York, N. Y., February 9, 1926, on Chester Lichtenberg's "Supervisory Systems for Electric Power Apparatus," by H. C. DonCarlos, in the July 1926, issue of the JOURNAL of the A.I.E.E., pages 671–2, under the heading, "Among the numerous remedies considered may be mentioned:" wherein plan *C*, of which the writer was credited with proposing, was exactly similar in circuit arrangement, to the neutralizing transformer protective system described by the above-mentioned authors.

The discussion at Niagara Falls, N. Y., May 25, 1926, of F. V. Smith's paper on "Automatic and Supervisory Control of Hydro Electric Stations," by C. F. Publow, in the October 1926, issue of the JOURNAL of the A.I.E.E., pages 1030–3, in the next to the last paragraph on page 1031 and on the next to the last paragraph on page 1032, wherein mention is made of these transformers previously referred to by Mr. DonCarlos.

The writer's United States Patent number 1,773,238 issued August 19, 1930, and Canadian Patent number 326,309 issued September 27, 1932.

The neutralizing transformer proposal discussed by DonCarlos and Publow was completed on July 1, 1926, under the writer's supervision, and from the standpoint of protection, the operation of the system has been satisfactory.

The design of neutralizing transformer disclosed in the patent, secures the closest possible coupling of primary and secondary windings and balance of all conductors or pairs in the secondary windings, relative to each other, the primary winding and to ground, as perfect as the inherent balance in the cable itself, so that the cable may be used for telephonic communication without mutual or extraneous interference.

E. E. George, in behalf of himself and coworkers, has very graciously acknowledged their error.

Very truly yours,

R. W. OSBORNE (A'18, M'31)

President, Osborne Electric Co., Ltd., Toronto, Canada.

President, Osborne Electric Corporation, Niagara Falls, N. Y.

To the Editor:

Since preparing the paper on "Pilot Wire Protection" published in November issue of ELECTRICAL ENGINEERING, R. W. Osborne has called attention to his usé of neutralizing transformers for protection of metering circuits in Canada nearly 10 years ago. While our application was developed independently, and was regarded as original by manufacturing, communication, and power companies, it seems that credit should go to Canada for the first use and public mention of neutralizing transformers in the power field.

We were too much interested in the merits of our discovery to note that another explorer had preceded us by 10 years.

Very truly yours,

E. E. GEORGE (A'20, M'29)

Supt. of Electrical Operation, Tennessee Electric Power Co., Chattanooga

Capacitor Motor With Double Cage Rotor

To the Editor:

The "Letter to the Editor" by Edward Bretch in the December 1935 issue of ELECTRICAL ENGINEERING, page 1422, implies that on the whole a double cage rotor in a capacitor type stator will not operate satisfactorily. While we have conducted no tests as yet, the following seems self-evident:

At any speed, the co-operation of the 2 stator windings with the rotor winding results in an elliptical field in the air gap. This elliptical field is equivalent to 2 unequal revolving fields turning in opposite directions. The rotor turns with the

stronger of these fields. As each of these fields produces similar effects to those in a polyphase motor, there is no difference in the reaction of the double cage rotor to them, except that its constants X_2 and r_2 each have different values in the 2 directions. Of course, just as in a polyphase motor, it probably will be necessary to maintain a certain relation between the 2 cage resistances and the leakage reactance of the inner cage in order to minimize or avoid the "dips" in the speed-torque curve.

The double cage machine does have a higher magnetic leakage (which does not manifest itself at starting and lower speeds) which tends to lower the power factor at rated speed, and to call for more flux per pole. But as the capacitance required for starting with given torque is not increased and may even be reduced, no additional microfarads need be purchased, though possibly a larger number may be necessary for the running condition. The lower rotor resistance loss of the double cage at rated speed will frequently make up for the increased iron loss which is due to the larger flux. The repulsion starting capacitor motor should be a high grade machine. However, it too has more leakage reactance and also a higher rotor resistance, more complication, and a higher cost, with probably more things to go wrong.

Yours very truly,

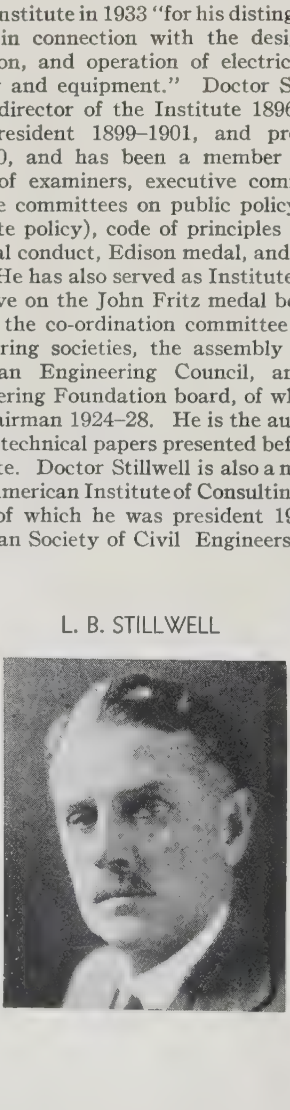
A. F. Puchstein (A'20, M'27)

Robbins & Myers, Inc.,
Springfield, Ohio

Personal Items

L. B. Stillwell (A'92, F'12, member for life, and past-president) consulting engineer, Princeton, N. J., has been awarded the A.I.E.E. Edison Medal for 1935 "for distinguished engineering achievements and his pioneer work in the generation, distribution, and utilization of electric energy." The medal, which was founded by friends and associates of the late Thomas A. Edison (A'84, M'84, HM'28) and is awarded annually for "meritorious achievement in electrical science, electrical engineering, or the electrical arts," will be presented to Doctor Stillwell during the A.I.E.E. winter convention at New York, N. Y., January 28–31, 1936. Doctor Stillwell was born at Scranton, Pa., March 12, 1863, and received the degrees of electrical engineer, master of science, and doctor of science from Lehigh University in 1885, 1907, and 1914, respectively, receiving also the degree of doctor of science from Wesleyan University in 1907. He entered the employ of the Westinghouse Electric and Manufacturing Company as assistant electrician in 1886, and in 1891 became chief electrical engineer, holding this position until 1897 when he was appointed electrical director of the Niagara Falls Power Company. Doctor Stillwell was active in the development of a-c systems at this time, and originated many important inventions. In 1900 he established a consulting engineering practice at New York, and has been engaged in the engineering work undertaken by a number of companies, including the Hudson and Manhattan Railroad; Erie Railroad; Interborough Rapid Transit Company; New York, New Haven and Hartford Railway Company; New York, Westchester, and Boston Railway Company; New York State Bridge and Tunnel Commission and the New Jersey Interstate Bridge and Tunnel Commission (in connection with the Holland Vehicular Tunnel), and, since 1927, the Port of New York Authority. At the time of the World War, he was a member of the National Research Council. In 1920 he was elected a trustee of Princeton University for life, and during the period 1921–23 was a member of the board of directors of the Chamber of Commerce of the United States. The president of the Niagara Falls Power Company awarded the Niagara medal to Doctor Stillwell in 1899, and the American Society of Civil Engineers conferred a medal upon him in 1929 "for leadership as chairman of Engineering Foundation in consolidating the research work of the Foundation and the founder societies." He received the Lamme medal of the Institute in 1933 "for his distinguished career in connection with the design, installation, and operation of electrical machinery and equipment." Doctor Stillwell was a director of the Institute 1896–99, a vice president 1899–1901, and president 1909–10, and has been a member of the board of examiners, executive committee, and the committees on public policy (now Institute policy), code of principles of professional conduct, Edison medal, and standards. He has also served as Institute representative on the John Fritz medal board of award, the co-ordination committee of the engineering societies, the assembly of the American Engineering Council, and the Engineering Foundation board, of which he was chairman 1924–28. He is the author of several technical papers presented before the Institute. Doctor Stillwell is also a member of the American Institute of Consulting Engineers, of which he was president 1918–19, American Society of Civil Engineers, Institution of Electrical Engineers (Great Britain), National Academy of Sciences, Royal Society of Arts (Great Britain), American Philosophical Society, and Franklin Institute.

L. B. STILLWELL



G. A. Campbell (A'03, F'13) research engineer, Bell Telephone Laboratories, Inc., New York, N. Y., has retired from active membership on the staff of the laboratories. Doctor Campbell was born at Hastings, Minn., and studied at Massachusetts Institute of Technology and Harvard University, receiving the degree of bachelor of science from the former and the degrees of bachelor of arts and master of arts from the latter in 1891, 1892, and 1893, respectively. He continued the study of mathematics and physics in Europe during the next 4 years, and in 1897 engaged in research problems in telephony with the American Telephone and Telegraph Company at New York. Doctor Campbell, independently of the late M. I. Pupin (A'90, F'15, HM'28, and past-president) also developed a theory of loading long lines by means of inductance in order to decrease attenuation, and while the patents on the coils were issued to Pupin, because of priority, the rules formulated by Campbell for the design and spacing of the coils were used from the beginning in the United States. Other problems with which Doctor Campbell was concerned include crosstalk, filters, and circuit stability, and he is credited with originating the articulation test used in telephone development work. Recently he was transferred to the Bell Telephone Laboratories, Inc. Several technical papers have been written by him. Commenting on his retirement, Dr. F. B. Jewett (A'03, F'12, and past-president) stated that Doctor Campbell's achievements in telephone transmission "entitle him beyond question to rank first among his generation of theoretical workers in electrical communication."

R. C. Putnam (A'26, M'34) who has been assistant professor of electrical engineering at Case School of Applied Science, Cleveland, Ohio, since 1928, recently was made associate professor. Professor Putnam holds the degrees of bachelor of arts from Butler College, bachelor of science in electrical engineering and electrical engineer from the University of Colorado, and master of science from Case School of Applied Science. He was a test engineer with the General Electric Company at Schenectady, N. Y., for one year before coming to Case School of Applied Science as an instructor in 1925. During 1933–34 he was chairman of the Cleveland Section of the Institute, and he is also a member of the Society for the Promotion of Engineering Education and the Illuminating Engineering Society.

Augustin Frigon (A'20) director of technical education for the province of Quebec and dean, Ecole Polytechnique, Montreal, Can., is one of 3 engineers named by the provincial government of Quebec to make up the recently authorized Quebec Electricity Commission. The commission

is empowered to hold inquiries into all matters pertaining to the supply of electricity in the province. Mr. Frigon, who was born at Montreal March 6, 1888, is a graduate of École Polytechnique, having received the degrees of bachelor of science, civil engineer, and electrical engineer. From 1910 to 1917 he was in charge of the electrical engineering laboratories of École Polytechnique, and then was given charge of the electrical engineering department. Among other work in which he was engaged during this time was that of electrical engineer for the Quebec Public Utilities Commission from 1911 to 1914. During 1920 to 1922 he was in Paris, France, as commissariat general du Canada, and since his return to Montreal has been dean of the school.

H. W. FISHER (A'95, F'12, and member for life) former technical director of the Standard Underground Cable Company and consulting electrical engineer of the General Cable Corporation, retired, and now resident at 549 Seventh Street South, St. Petersburg, Florida, has been invited to give talks on electric cables at the University of Florida and at Georgia School of Technology. Prior to his retirement in 1930, Mr. Fisher had been intimately associated for some 40 years with the design, manufacture, and application of electric cables and active in research and experimental work contributing essentially to their development. He was a member of the Institute's committees on standards 1914–22, and transmission and distribution 1915–19, and was representative on the U.S. national committee of the International Electrotechnical Commission 1919–26.

A. E. KENNELLY (A'88, F'13, HM '33, Life Member, and past-president) professor emeritus of electrical engineering, Harvard University and Massachusetts Institute of Technology, Cambridge, has been awarded the Mascart medal for 1936. The medal, established in honor of one of the founders of the Société Français des Électriciens, is awarded triennially by the society to a scientist or engineer who is distinguished by a group of works on pure or applied electricity. The first award was made in 1924. Doctor Kennelly is well known for his work on electrical and magnetic magnitudes and units, and a paper by him on the new system adopted by the International Electrotechnical Commission was published in the December 1935 issue of ELECTRICAL ENGINEERING. He has long been active in Institute affairs. A brief biographical sketch of Doctor Kennelly, indicating the scope and variety of his professional career, appeared in the July 1935 issue in connection with his election to honorary presidency of the U.S. National Committee of the International Electrotechnical Commission.

E. W. GREENFIELD (A'34) who recently received a doctorate degree for paper cable research at The Johns Hopkins University, is now dielectric research engineer for the Anaconda Wire and Cable Company at

A. E. KENNELLY

Hastings-on-Hudson, N. Y. He is the author of several technical papers on dielectrics, one of which he was a co-author being presented to the Institute. Doctor Greenfield is also a member of the American Physical Society and Society of Sigma Xi, and is a member of the committee on electrical insulation of the National Research Council.

WILLIAM MCCLELLAN (A'07, F'12, and past-president) president of the Potomac Electric Power Company, Washington, D. C., has been made president of the Washington Railway and Electric Company. Doctor McClellan in the past has been connected with a number of engineering firms, and in 1929 was elected vice president of Stone and Webster Engineering Corporation. He has served on many of the Institute's committees, now being representative on the American Engineering Council assembly, and was Institute manager 1912–15, vice president 1915–17, and president 1921–22.

F. P. QUIGLEY (M'33) former engineer with the Federal Power Commission, has been made regional liason officer in the procurement division of the U.S. Treasury Department, and has his headquarters at Denver, Colo. Mr. Quigley, who was engaged in making appraisal studies for the commission, is now concerned with the coordination of all Federal agencies operating in the states of Colorado, Wyoming, and Montana under funds provided by recent legislation. He is also a member of the American Society of Naval Engineers.

W. E. WICKENDEN (A'07, M'13) president, Case School of Applied Science, Cleveland, Ohio, has been appointed a member of the organization committee for the Great Lakes Exposition, which is to be held at Cleveland during the summer of 1936. Doctor Wickenden recently received the Lamme Medal of the Society for the Promotion of Engineering Education, in connection with which a biographical sketch was published in ELECTRICAL ENGINEERING for September 1935, page 1019.

J. B. FISKEN (A'03, F'13, member for life, and past vice president) consulting engineer, The Washington Water Power Company, Spokane, has been appointed chairman of the general committee of the engineering and operation section of the Northwest Electric Light and Power Association. Mr. Fisken, who has served on several Institute committees, was a manager of the Institute 1916–19 and vice president 1919–20.

H. B. DATES (A'98, F'32, and member for life) professor and head of the department of electrical engineering, Case School of Applied Science, Cleveland, Ohio, has been elected secretary-treasurer of the U.S. National Committee of the International Commission on Illumination, and was also appointed director of the secretariat on lighting practice. He is a member of the Institute's committee on the production and application of light.

ERICH HAUSMANN (A'06, F'18) professor of physics and electrical communication, and dean of graduate study, Polytechnic Institute of Brooklyn, N. Y., has been elected chairman of the New York State Board of Examiners for Professional Engineers for the ensuing year. Dean Hausmann was a member of the Institute's board of examiners 1920–30, and was a member of the committee on communication 1927–31.

T. F. MCMAINS (A'34) former chief operator at Wichita Falls, Texas, for the Western Union Telegraph Company, has been made engineering assistant in the office of the vice president in charge of the traffic department at New York, N. Y., where he will specialize in general traffic supervision. Mr. McMains has held various positions with the company in Oklahoma and Texas since he was graduated from the University of Illinois in 1927.

JOSEPH SACHS (A'92, F'12, and member for life) chief engineer, electrical division, Colt's Patent Fire Arms Manufacturing Company, Hartford, Conn., recently was made chairman of the fuse section of the National Electrical Manufacturers Association. Mr. Sachs served on the safety codes committee of the Institute 1924–27, and on the instruments and measurements committee 1924–25.

C. S. THORN (M'34) who has been chief engineer of the Birmingham (Ala.) Electric Company, recently was elected vice president in charge of operation. Mr. Thorn came to the company in 1927 as supervisory engineer, and 2 years later was appointed chief engineer, operating the electric distribution system, street railway system, and steam heating system in Birmingham.

M. T. CRAWFORD (A'07, F'22) assistant chief engineer, Puget Sound Power and Light Company, Seattle, Wash., has been appointed chairman of the transmission and distribution committee of the Northwest Electric Light and Power Association. A biographical sketch of Mr. Crawford was given in ELECTRICAL ENGINEERING for December 1935, page 1423.

A. D. LUNDY (A'03, F'20, and member for life) secretary and treasurer, Sargent and Lundy, Inc., Chicago, Ill., has retired. Mr. Lundy, who received degrees from Princeton University and Cornell University, has been

a member of the firm since 1891, having previously been with the Sprague Electric Railway and Motor Company and the Sprague Electrical Equipment Company.

J. F. Lincoln (A'08, M'20, and past manager) president, The Lincoln Electric Company, Cleveland, Ohio, has been appointed a member of the organization committee for the Great Lakes Exposition, which is to be held at Cleveland during the summer of 1936. Mr. Lincoln was a manager of the Institute 1920–24.

Miguel Wiewall, Jr. (A'29) instructor in electrical engineering at the University of Puerto Rico, Mayaguez, is taking graduate courses at Harvard University, Cambridge, during a sabbatical leave. He was counselor of the Student Branch at the University of Puerto Rico during the year 1934–35.

S. J. Levine (A'32) former student engineer with the General Electric Company at Schenectady, N. Y., is now at Bloomfield, N. J., as designing engineer. Mr. Levine, who was a member of the executive committee of the Schenectady Section, recently presented a paper on analysis of the induction motor to the Institute.

C. G. Watkins-Ball (A'35) who has been in the motor engineering department of Metropolitan-Vickers Electrical Company, Ltd., Manchester, England, is now with Metropolitan-Vickers Electrical Export Company, Ltd., at Johannesburg, South Africa.

W. S. G. Dulin (A'22) who has been general plant manager at Charleston for the Chesapeake and Potomac Telephone Company of West Virginia, is now plant supervisor at Washington, D. C., for the Chesapeake and Potomac Telephone Company.

John West (A'10, M'28) president, Fall River (Mass.) Electric Light Company, has been designated a regional executive of the New England Power Association, a position which has managerial functions over groups of operating companies.

Randolph Eide (A'23, M'32) president, The Ohio Bell Telephone Company, Cleveland, has been appointed a member of the organization committee for the Great Lakes Exposition which is to be held at Cleveland during the summer of 1936.

Otto Brune (A'31) former instructor at Massachusetts Institute of Technology, Cambridge, has become connected with the South African General Electric Company, Ltd., as electrical engineer, and is at Johannesburg, Union of South Africa.

A. G. L. McNaughton (A'11) major general, C.B., C.M.G., D.S.O., who has been chief of general staff, Department of National Defense, Ottawa, Ont., Can., has been made president of the National Research Council of Canada at Ottawa.

E. W. Palmrose (A'32) former draftsman for Southern Pacific Golden Gate Ferries, Ltd., San Francisco, Calif., is now an operator in the department of operation and maintenance of the Panama Canal at Gatun, C. Z.

W. A. Manfield (A'32) former works manager of the Conduits Company, Ltd., Toronto, Ont., Can., which recently was merged with Conduits National Limited, has organized a new company, Conduits and Electric Raceways Limited, at Toronto.

J. D. McMynn (A'35) formerly employed by the West Kootenay Power and Light Company at Trail, B. C., Can., has entered the student test course of the Canadian General Electric Company at Peterboro, Ont.

C. J. Breitwieser (A'33) formerly technical director, United Sound Productions Company, Los Angeles, Calif., is now engineer in charge of production and development, Conducto-Therm Corporation, Los Angeles.

C. M. Hutchins (A'35) who has been a student engineer at Schenectady, N. Y., for the General Electric Company, is now a student patent attorney in the company's patent department at Washington, D. C.

H. A. Moench (A'31) is doing graduate work in the department of electrical engineering at the University of Michigan, Ann Arbor, during a leave of absence from his position as instructor at Rose Polytechnic Institute, Terre Haute, Ind.

F. R. Phillips (M'27) president of the Philadelphia Company and the Pittsburgh Railways Company, Pittsburgh, Pa., recently was elected to the board of directors of the Byllesby Engineering and Management Corporation.

W. T. Gray, Jr. (A'29) who recently received the degree of doctor of philosophy in physics at Northwestern University, is now employed as physicist by the Corning (N. Y.) Glass Works.

J. G. Jackson (A'08) director of engineering, Square D Company, Detroit, Mich., recently was made chairman of the small air circuit breaker section of the National Electrical Manufacturers Association.

W. N. Clark (A'05) president, Southern Colorado Power Company, Pueblo, recently was elected to the board of directors of the Byllesby Engineering and Management Corporation.

Eric Lewis (A'30) who has been a representative for the English Electric Company, Ltd., at Tokyo, Japan, is now with the Jardine Engineering Corporation, Ltd., at Shanghai, China.

M. A. Sorieri (A'30) former cable tester at New York, N. Y., for the American Telephone and Telegraph Company, has been transferred to Buffalo as a technical employee.

E. H. Schoenfeld (A'35) who has been receiving engineer for RCA Communications, Inc., at Point Reyes station, Calif., is now with Heintz and Kaufman, Ltd., San Bruno, Calif., as engineer.

R. J. Weesner (A'35) former wireman with the American Sheet and Tin Plate Company at Gary, Ind., is now engaged in electrical testing by the Reliance Electric and Engineering Company, Cleveland, Ohio.

F. O. Urban (A'31) formerly in the air conditioning department of the General Electric Company at Schenectady, N. Y., is now in the commercial engineering division of the department at Bloomfield, N. J.

R. F. Pack (A'11, M'12) president, Northern States Power Company, Minneapolis, Minn., recently was elected to the board of directors of the Byllesby Engineering and Management Corporation.

Thomas Fitzgerald (A'02) vice president and general manager, Pittsburgh (Pa.) Railways Company, recently was made chairman of the new safety committee of the American Transit Association.

F. E. Snell (A'23) superintendent of power, Cleveland (Ohio) Railway Company, has been appointed a member of the new safety committee of the American Transit Association.

R. G. Macy (A'23, M'25) special adviser to the Federal government on utility questions, has been appointed chief engineer of the State Board of Public Utility Commissioners of New Jersey.

O. H. Caldwell (A'13, M'22) editor and treasurer of *Radio Today*, New York, N. Y., has been re-elected a trustee of the New York Museum of Science and Industry.

J. M. Kopper III (A'34) is now employed in the research laboratory of the National Advisory Committee for Aeronautics at Langley Field, Va.

W. W. Kissinger (A'35) is now assistant draftsman for the soil conservation service of the U.S. Department of Agriculture, Washington, D. C.

W. J. Berry (A'31) manager of The Western Telephone Corporation who has been at Watonga, Okla., is now at Kingfisher, Okla.

W. H. Manfield (A'27) division plant engineer, Southern Bell Telephone and Telegraph Company, who has been at Louisville, Ky., is now at Jackson, Miss.

L. M. Sorenson (A'34) engineer formerly with Blocksom and Company, Michigan City, Ind., is now employed by the Beloit (Wis.) Iron Works.

J. H. Stresen-Reuter (A'35) who has been employed by the General Electric Company at Chicago, Ill., is now with The Detroit (Mich.) Edison Company.

R. G. Lindquist (A'35) who is employed by the West Penn Power Company, has been transferred from Kittanning, Pa., to Vandergrift.

Robert Soutter, Jr. (A'32) sales engineer of the Okonite-Callender Company, Inc., who has been at Paterson, N. J., has been transferred to Boston, Mass.

G. T. Royden (A'19, M'31) Mackay Radio and Telegraph Company, who has been division engineer at San Francisco, Calif., is now at New York, N. Y.

Newell Parker (A'31) is now an electrical engineer in the construction department of the Public Service Company of Colorado, Denver.

F. A. Hoeke (M'34) engineer with the General Electric Company, has been transferred from Birmingham, Ala., to Knoxville, Tenn.

A. F. Hibbeler (A'26) formerly assistant electrical engineer with Fansteel Products Company, North Chicago, Ill., is now with Ariston Laboratories, Chicago.

N. L. Gregg, Jr. (A'34) formerly with the Union Power Company, Mullens, W. Va., is now with the West Virginia Engineering Company, Bluefield.

H. W. Berkley (A'17, M'26) is now connected with the Westinghouse Electric and Manufacturing Company at Boulder City, Nev.

P. S. Grobler (A'34) former electrical engineer, Rustenburg Municipality, South Africa, is now at Alberton with the Alberton Health Committee.

A. E. Capon (A'32) has accepted a position with the Metropolitan Water District of Southern California, Los Angeles, as junior electrical engineer.

J. F. Kruszka (A'35) appraisal engineer, Jensen, Bowen, and Farrell, who has been at Newark, N. J., is now at Ann Arbor, Mich.

Burnham Cogswell (A'22, M'34) field engineer, General Electric Company, has been transferred from Rochester, N. Y., to Buffalo.

Clare Anderson (A'26) is now a sales engineer with the Westinghouse Electric and Manufacturing Company, Newark, N. J.

E. A. Johnson (A'29) is now assistant electrical engineer in the procurement division of the U.S. Treasury Department, Washington, D.C.

G. C. Fay (A'34) Harbison-Walker Refractories Company, has been transferred from Clearfield, Pa., to Pittsburgh, Pa.

J. G. Tankovich (A'33) is now employed in the municipal light plant at Columbus, Ohio.

R. S. Stokan (A'34) is now in the U.S. Engineers Department at Fort Peck, Mont.

Obituary

Edwin Wilbur Rice, Jr. (A'87, M'88 F'13, HM'33, member for life, and past-president) honorary chairman of the board of directors and former president of the General Electric Company, Schenectady, N. Y., died November 25, 1935. Doctor Rice was born at La Crosse, Wis., May 6, 1862, and while attending a Philadelphia, Pa., school in 1876 had for a teacher Elihu Thomson (A'84, F'13, HM'28, member for life, and past-president) who entered electrical manufacturing in 1880, taking Doctor Rice with him. Three years later the Thomson-Houston Company was established at Lynn, Mass., and Doctor Rice became plant superintendent. This company was consolidated with the Edison General Electric Company in 1892 to form the present General Electric Company, and Doctor Rice became technical director of the new company. In 1896 he was made vice president in charge of manufacturing and engineering, and in 1913 became president of the company, holding this office until 1922 when he was elected honorary chairman of the board of directors. Doctor Rice received the degrees of bachelor and master of arts from Central High School, Philadelphia, in 1880 and 1885, respectively; the honorary degrees of master of arts from Harvard University in 1903, doctor of science from Union College in 1906, and from the University of Pennsylvania in 1924, and doctor of engineering from Rensselaer Polytechnic Institute in 1917. He received more than 100 patents covering a wide range of subjects, including distribution systems, a-c and d-c generators and motors, oil switches, protective devices, lamps, transformers, and train control systems. He also was chiefly responsible for the establishment of the company's research laboratories, which he recommended in 1900. In addition to his technical work, Doctor Rice indorsed and promoted many modern forms of industrial organization and methods of advancing employees' welfare. The Third Order of the Rising Sun with Cordon was conferred upon him by the emperor of Japan, and he was awarded the decoration of chevalier of the Legion of Honor by France. In 1931 the Edison medal of the Institute was presented to him "for his contributions to the development of electrical systems and apparatus and his encouragement of scientific research in industry." Doctor Rice was president of the Institute during the year 1917–18, and served on the following Institute committees: Edison medal, 1916–21; executive, 1917–18; public policy (now Institute policy) 1914–16 and 1917–18; research, 1920–22 and 1924–28; licensing of engineers, 1924–29; economic status of the engineer, 1931–35. He also was Institute representative on the following: Engineering Foundation board, 1919–24; John Fritz medal board of award, 1918–21; American Engineering Council, 1923–29; engineering division of the National Research Council, 1924–27; U.S. national committee of the International Electrotechnical Commission, 1926–30; and Hoover medal board of award, 1931–35. Doctor Rice was a member of the Institution of Civil Engineers and the Institution of Electrical Engineers, both of Great Britain, the Society of Illuminating Engineers, Tau Beta Pi, and many other organizations.

A. Raymond Tremaine (A'16, M'19) vice president, The Utility Management Corporation, New York, N. Y., died August 25, 1935, according to word just received at Institute headquarters. Mr. Tremaine was born at Batavia, N. Y., January 8, 1877, and was a graduate of the Bliss Electrical School. Following several years of construction work, in 1901 he became electrical superintendent of the Hydraulic Electric Company, LeRoy, N. Y., and later became general superintendent. During 1907 he was employed by the Niagara Falls (N. Y.) Lighting Company, and in 1908 became general superintendent and engineer of the Depew and Lancaster and Light, Power, and Conduit Company, Lancaster, N. Y., holding this position until he was made manager and chief engineer in 1916. He was appointed president and general manager in 1926, and the following year accepted the position of general manager of the New York State group of the Associated Gas and Electric System. In 1930 he was made contact representative with the Associated system in Pennsylvania and New Jersey for The Utilities Management Corporation.

Robert Cowl Smith (A'17, M'29) chief civil and electrical engineer, public service department, City of Glendale, Calif., died November 12, 1935. He was born May 6, 1894, at Wheeling, W. Va., and held several positions in civil and electrical engineering work before he became electrical draftsman of the Llewellyn Iron Works at Los Angeles, Calif., in 1919. The following year he became senior electrical and mechanical draftsman for the public service department of the city of Glendale. Two years later he was made civil and electrical engineer, and in 1923 was appointed chief engineer. The department has charge of the municipally owned and operated water, power, and light system, and Mr. Smith supervised the plans for improvements made in the system since that time.

Sataro Fukunaka (M'21) director, Nippon Electric Power Company, Ltd., Osaka, Japan, died June 17, 1935, according to word recently received at Institute headquarters. He was born at Tokyo January 18, 1883, and studied electrical engineering at Tokyo Imperial University, with further studies in Europe during 1910–11. He was employed in responsible positions by the Uji-gawa Electric Company, Osaka, prior to becoming chief engineer of the Nippon Electric Power Company in 1920, at which time the company was engaging in the construction of a 220 mile transmission system. Mr. Fukunaka held this position until 1926, when he was made director.

Charles R. Blanchard (A'13) electrical engineer, General Electric Company, Pittsfield, Mass., died November 29, 1935. He was born at Farmington, Pa., October 17, 1878, and received the degree of bachelor of science in electrical engineering at Pennsylvania State College in 1908. At that time he entered the employ of the General Electric Company as a student at Pittsfield, and the following year entered the testing laboratories, taking charge of the experimental work on insulating materials in 1911.

John Mollison Brodie (A'12, M'13) senior mechanical engineer, chemical warfare service, U.S. Army, at the Edgewood Arsenal, Edgewood, Md., died suddenly

November 21, 1935. He was born at Coleman's Falls, Va., March 20, 1885, and was graduated with the class of 1905 from Virginia Polytechnic Institute, receiving the degree of bachelor of science in electrical engineering. He then entered the student course of the General Electric Company, and shortly was made assistant engineer in the instrument transformer department at West Lynn, Mass. He later became designing engineer, but during the World War was a lieutenant in the U.S. Navy, and subsequently became designing and later chief engineer of the Kinney Manufacturing Company, Boston. He had been at the Edgewood Arsenal since 1926.

Marvin Nathan Fellman (A'33) cadet engineer, Philadelphia Electric Company, Philadelphia, Pa., died October 9, 1935. He was born at Philadelphia, August 7, 1911, and was graduated from the University of Pennsylvania in 1932 with the degree of bachelor of science in electrical engineering. Since graduation he had been employed by the Philadelphia Electric Company.

Membership

Recommended for Transfer

The board of examiners, at its meeting held December 18, 1935, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Crawford, W. E., consulting engr., A. O. Smith Corp., Milwaukee, Wis.
Doggett, L. A., prof. of E.E., Pennsylvania State College, State College.
George, E. E., supt. of system operation, Tennessee Elec. Pwr. Co., Chattanooga.
Kintner, S. M., vice president, Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.
Krug, Frederick, vice president and general mgr., Porto Rico Railway Lt. and Pwr. Co., San Juan.
Seeger, E. W., asst. chief engr., Cutler-Hammer, Inc., Milwaukee, Wis.

6 to Grade of Fellow

To Grade of Member

Boland, E. J., meter specialist, General Elec. Co., Schnectady, N. Y.
Brown, D. S., mgr., elec. production, Union Gas and Elec. Co., Cincinnati, Ohio.
Clark, W. N., president and mgr., Southern Colorado Power Co., Pueblo.
Coleman, G. G., engr., preliminary plans, Chesapeake and Potomac Tel. Co., Washington, D. C.
dePapp, E., E.E., Indianapolis Pwr. and Lt. Co., Indianapolis, Ind.
Elley, A. C., E.E., Yates American Machine Co., Beloit, Wis.
Ellmann, J. I., president, Ellmann, Inc., Washington, D. C.
Geiger, D. G., transmission engr., Bell Tel. Co. of Canada, Toronto, Ont.
Hamill, S. M., Jr., asst. supt. elec. operating dept., Union Gas and Elec. Co., Cincinnati, Ohio.
Hemsley, S. H., asst. transformer design engr., Messrs. Bruce Peebles & Co. Ltd., East Pilton, Edinburgh, Scotland.
Kramer, C. H., chief pwr. supervisor, Union Gas and Elec. Co., Cincinnati, Ohio.
Leibing, S. C., sales engr., General Elec. Co., Indianapolis, Ind.
Lempke, W. J., division plant supt., Am. Tel. & Tel. Co., Chicago, Ill.
MacNeill, J. B., mgr., switchgear engg. dept., Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.
Murrough, J. P., asst. E.E., Nova Scotia Pwr. Commission, Halifax, Nova Scotia, Can.
Nelson, E. E., general supt., Blackstone Valley Gas and Elec. Co., Pawtucket, R. I.
Newman, L. L., supt. of distribution, New Orleans Public Service Co., New Orleans, La.
Puente, M. de J., chief engr., Havana Water Works, and supervising engr., National Hotel of Cuba, Havana, Cuba.
Richards, H. E., assoc. prof. of E.E., Northeastern Univ., Boston, Mass.
Ricker, C. W., prof. of E.E., Tulane Univ., New Orleans, La.
Rubinstein, H. W., production engr., Globe Union Mfg. Co., Milwaukee, Wis.
Stephenson, W. B., general plant extension engr., Southwestern Bell Tel. Co., St. Louis, Mo.
Stevens, G. D., engr., elec. engg. dept., Consumers Pwr. Co., Jackson, Mich.
Stewart, R. B., patent lawyer, National Press Bldg., Washington, D. C.
Trussler, L. C., div. service inspector, long lines plant dept., Am. Tel. and Tel. Co., Denver, Colo.
Tuckerman, L. P., radio engr., Federal Telegraph Co., Newark, N. J.
Twiss, R. H., application engr., General Elec. Co. New York, N. Y.
White, C. J., chief engr., Callaway Mills, LaGrange, Ga.

28 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Jan. 31, 1936, or Mar. 31, 1936, if the applicant resides outside of the United States or Canada.

Arnold, E. H. (Member), Western Elec. Co., Kearny, N. J.
Asling, J. H., Crosley Radio Corp., Cincinnati, O.
Boltz, C., Cleveland Elec. Ill. Co., O.
Brinker, W. E., Westinghouse Elec. & Mfg. Co., St. Louis, Mo.
Bruun, B. N. (Member), Gibbs & Hill Inc., New York, N. Y.
Bush, F. W., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Callow, M. E., Anaconda Copper Mining Co., Butte, Mont.
Case, N. M., Gen. Elec. Co., Pittsfield, Mass.
Christensen, P. L., Gen. Elec. Co., Pittsfield, Mass.
Coolbroth, E. L. (Member), Am. Tel. & Tel. Co., New York, N. Y.
Cooper, J. B., Gen. Elec. Co., Pittsfield, Mass.
Corbin, R. C., Burns & McDonnell Engg. Co., Kansas City, Mo.
Crevasse, J. N., Gen. Elec. Supply Corp., Jacksonville, Fla.
Daily, C. S., Jr., 7 Chestnut St., Islip, L. I., N. Y.
Daley, J. L., Yale Univ., New Haven, Conn.
de Lascurain, M. M., Jr., Gen. Electric, S. A., Mexico, D. F., Mexico.
Denton, L. E., Houston Lt. & Pwr. Co., Texas.
Dock, A. F., N. Y. Tel. Co., New York, N. Y.
Falcone, A. J., N. Y. Edison Co., Inc., New York, N. Y.
Faller, G. W. (Member), Pub. Serv. Co. of Colo., Denver.
Fein, F. P., Union Gas & Elec. Co., Cincinnati, O.
Fox, F. K., Western Vegetable Oils Co., Oakland, Calif.
Galbraith, H. C. (Member), Am. Tel. & Tel. Co., Chicago, Ill.
Goldner, G. W., James R. Kearney Corp., St. Louis, Mo.
Green, E. L., Jr., N. Y. Edison Co. Inc., New York, N. Y.
Grimmer, E. J., Westinghouse Elec. & Mfg. Co., Sharon, Pa.
Grover, J. B., N. Y. & Q. Elec. Lt. & Pwr. Co., Flushing, N. Y.
Gunn, D. (Member), Safe Harbor Water Pwr. Corp., Baltimore, Md.
Heitsmith, W. J. (Member) Bell Tel. Lab., New York, N. Y.
Hennig, W. E., 1510 N. 57th St., Milwaukee, Wis.
Holmstrom, G. C., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Hope, E. M., U.S. Army Engineers, Portland, Oregon.
Hornbecker, G. A., Chase Co. Inc., Waterbury, Conn.
Huber, R. A. M., Cincinnati Milling Machine Co., O.
Hutchinson, C., Tenn. Pub. Serv. Co., Knoxville.
Jamison, B. C. (Member), Am. Tel. & Tel. Co., Chicago, Ill.
Johnson, W. I., N. Y. Edison Co., Inc., New York, N. Y.
Jones, O. N. (Member), Walter P. Ambos Co., Cleveland, O.
Kaegi, E., Am. Brown Boveri Elec. Corp., Camden, N. J.
Kamenka, C. J., Wingdam Mine Camp, Wingdam, B. C., Can.
Kimball, R. L., Fed. Pwr. Commission, Washington, D. C.
Labaugh, J. M., Bell Tel. Lab., New York, N. Y.
Laub, H. (Member), c/o Charles Engelhard Concern, Newark, N. J.
Leitzell, R. S., N. Y. Edison Co. Inc., New York, N. Y.
Ludwig, N. C., Lewis Inst., Chicago, Ill.
Mann, D. H. (Member), Bell Tel. Lab. Inc., New York, N. Y.
Manning, E. L., Gen. Elec. Co., Schenectady, N. Y.
Manucia, J. T., 330 Maujer St., Brooklyn, N. Y.
Maxwell, M. V. (Member), Bureau of Reclamation, Denver, Colo.
Merchant, W. J., B. & O. R. R., Stapleton, S. I., N. Y.
Michel, P. C., Gen. Elec. Co., Schenectady, N. Y.
Miles, M. L., N. Y. Edison Co. Inc., New York, N. Y.
Morris, C. H., Western Factory Insurance Assn., Chicago, Ill.
Munson, S. H., Am. Tel. & Tel. Co., Kalamazoo, Mich.
Nordquist, C. A., Rwy. & Industrial Engg. Co., Chicago, Ill.
Price, F. W., Westinghouse Elec. & Mfg. Co., Philadelphia, Pa.
Reed, G. M., Gen. Elec. Co., Philadelphia, Pa.
Reynolds, D. J., Kelley Koett Mfg. Co., Ludlow, Ky.
Rhodes, G. L., New Orleans Pub. Serv. Co., New Orleans, La.
Ringland, W. L., Allis-Chalmers Mfg. Co., W. Allis, Wis.
Rowan, E. W., Monmouth Beach, N. J.
Ruth, H. G., Westinghouse Elec. Supply Co., Reading, Pa.
Schwyter, E. M. (Member), Wilmington Trade School, Del.
Smith, W. H. W., 157 Foxhurst Road, Rockville Center, L. I., N. Y.
Strong, B. J., R. C. M. P. Barracks, Regina, Sask., Can.
Thatcher, P., Bulldog Elec. Products Co., Toledo, O.
Tolmie, J. R. (Member), Pacific Tel. & Tel. Co., Seattle, Wash.
Tradup, A. (Member), Bell Tel. Lab., New York, N. Y.
Turner, R. W., Houston Lt. & Pwr. Co., Texas.
Van Vranken, W. P., Brooklyn Edison Co., N. Y.
Walker, W. W., Weston Elec. Inst. Corp., Newark, N. J.
Weinheimer, C. M., Detroit Elec. Furnace Co., Mich.
Wyckoff, H. J. (Member), Detroit Edison Co., Mich.
Weins, J. F., City of Detroit, Pub. Lt. Comm., Detroit, Mich.
Yule, J. T., Pub. Serv. Co. of Colo., Fort Collins.

75 Domestic

Foreign

Dadashev, M. R., Energetical National Economy Baku, U. S. S. R.
Park, J. G. (Member), Electricity Board, Town Hall, Banbridge, County Down, Northern Ireland.
Parshad, Har, P. W. O. Elec. Branch, Dyallpur, (Punjab), India.
Sain, G., Punjab Elec. Pwr. Co. Ltd., Montgomery, Punjab, India.
Schindler, A. F., Univ. Lausanne, Switzerland.
Sethi, D. R., P. W. D. B. & R., Jullundur (Punjab), India.

6 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Blanc, Victor, 153 Boulevard Lefebvre, Paris, France.
Chiofalo, J., 203 Graham Ave., Brooklyn, N. Y.
Crite, Mitchel, 32 E. 126th St., New York, N. Y.
Ghosh, K. C., c/o Compagnia Generale Di Elettricity, 34 Via Borgognone, Milan, Italy.
Golikoff, A., Main P. O. Gen. Del., Moscow, U. S. S. R.
Kimball, Gordon S., 154 Elmer Ave., Schenectady, N. Y.
Nelson, Charles J., 1515 N. Lotus Ave., Chicago, Ill.
Rozelle, P. M., 2018 Chestnut St., Harrisburg, Pa.
Soskin, Samuel B., 1141 S. Central Park, Chicago, Ill.
Spiegel, William F., 7 Stegman Court, Jersey City, N. J.

10 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

CATHODE-RAY TUBE at WORK. By J. F. Rider, published by the author at 1440 Broadway, N. Y., 1935. 322 p., illus., 9x6 in., cloth, $2.50. A practical, nonmathematical exposition of the applications of the cathode-ray oscillograph in radio work, especially in the servicing of receivers and the observation of electrical phenomena associated with receiving, amplifying, and transmitting.

DIESEL ENGINES. By J. W. Anderson. N. Y. and Lond., McGraw-Hill Book Co., 1935. 491 p., illus., 9x6 in., cloth, $5.00. A description of the various types of engines in use in America, and some European examples, classified according to their applications.

ELEMENTS of MACHINE DESIGN. By D. S. Kimball and J. H. Barr. 3 ed. N. Y., John Wiley & Sons, 1935. 476 p., illus., 9x6 in., cloth, $4.00. No radical changes have been made in the third edition of this text, but each topic has been brought up to date, new subject matter added, and some obsolete sections eliminated.

ENAMELS, the Preparation, Application, and Properties of Vitreous Enamels. By A. I. Andrews. Champaign, Ill., Twin City Printing Co., 1935. 410 p., illus., 9x6 in., cloth, $5.00. A comprehensive, systematic account of theory and processes, covering the industry in a practical, yet scientific manner.

FINANCIAL INCENTIVES, a Study of Methods for Stimulating Achievement in Industry. (N.I.C.B. Studies, No. 217). N. Y., National Industrial Conference Board, 1935. 47 p., tables, 9x6 in., paper, $1.50. This study reviews the experience of industrial concerns in operating wage incentive plans under the new conditions, describes the changes that have been necessary, and discusses the probable future rôle of incentives.

Great Britain, Dept. of Scientific and Industrial Research, Medical Research Council. EFFECT of LIGHTING on EFFICIENCY in ROUGH WORK (TILE PRESSING). By S. Adams. Joint Report of the Industrial Health Research Board and the Illumination Research Committee. Lond., His Majesty's Stationery Office; obtainable from British Library of Information, N. Y. 1935. 12 p., illus., 10x6 in., paper, 4d. Reports an investigation of the effect of increasing the intensity of illumination in the case of perfectly simple occupations.

INDUSTRIAL ELECTRONICS. By F. H. Gulliksen and E. H. Vedder. N. Y., John Wiley & Sons, 1935. 245 p., illus., 9x6 in., cloth, $3.50. A description of most of the important industrial applications of electronic devices, discussing briefly the characteristics of electronic tubes and the fundamental circuits, and describing the use of electron tubes for indicating, controlling, and regulating many industrial processes.

METALLIC ARC WELDING. By H. Harris. N. Y., Longmans, Green & Co.; Lond., Edward Arnold & Co., 1935. 199 p., illus., 10x6 in., cloth, $6.00. A survey of arc welding, intended especially to call attention to its usefulness, which describes the process and equipment, methods of testing welds, and the influence of oxygen and nitrogen.

MODERN USES of NONFERROUS METALS. (Seeley W. Mudd Fund) ed. by C. H. Mathewson. 1st ed. N. Y., American Institute of Mining and Metallurgical Engineers, 1935. 427 p., illus., 8x6 in., cloth, $3.00 to nonmembers of A.I.M.M.E.; $1.00 to members. An authoritative introduction for the young metallurgist and nontechnical reader to the sources, properties, and uses of the nonferrous metals.

PHYSICS. By E. Hausmann and E. P. Slack. N. Y., D. Van Nostrand Co., 1935. 776 p., illus., 9x6 in., cloth, $4.00. A thorough course in the essentials of physics for college students preparing for scientific or engineering careers.

RELAY SYSTEMS, Theory and Application. By I. T. Monseth and P. H. Robinson. N. Y. and Lond., McGraw-Hill Book Co., 1935. 549 p., illus., 9x6 in., cloth, $6.00. This is intended to be a complete treatise on the theory and application of electric relays, giving a practical system of fault calculations for all arrangements of system connections and all types of short circuits, and discussing relay systems at length.

MITTEILUNGEN des FORSCHUNGSINSTITUTS für MASCHINENWESEN beim BAUBETRIEB, Heft 7, ed. by G. Garbotz, Technische Hochschule Berlin. UNTERSUCHUNG der ARBEITSBEDINGUNGEN für den ELEKTRISCHEN ANTRIEB von ABSATZWEISE ARBEITENDEN BAGGERN. By W. Penzien. Berlin, VDI-Verlag, 1935. 38 p., illus., 12x8 in., paper, 10.75 rm. Describes fully the results of a study of 20 electrically driven excavators, representing 4 common types, and covers power requirements and design.

SCHWEIZ. VERBAND für die MATERIALPRÜFUNGEN der TECHNIK. Bericht Nr. 29 (Bericht Nr. 83 der Eidg. Materialprüfungsanstalt). BEITRÄGE zur KENNTNIS der SPANNUNGSVERTEILUNG in PRISMATISCHEN und KEILFÖRMIGEN KONSTRUKTIONSELEMENTEN mit QUERSCHNITTÜBERGÄNGEN. By R. V. Baud. Zürich, November 1934. 72 p., illus., 12x8 in., paper, apply. Describes experimental investigations of the stress distribution in beams with varying cross sections, in the pole fastenings of dynamos and motors, in gear teeth, and in screws, using photoelastic methods from which data of practical value were obtained.

International Conference on Physics, Lond., 1934. International Union of Pure and Applied Physics. REPORTS on SYMBOLS, UNITS and NOMENCLATURE, published by the Physical Society, Lond.; printed at the University Press, Cambridge (England) 1935. 40 p., illus., 10x7 in., cloth, $1.20. The full reports approved at the 1934 meeting, which included recommendations on the standard thermal unit, electromagnetic units, thermodynamic symbols, and on future work of the committee on symbols, units, and nomenclature, and including also papers on the definitions of the magnetic units, on the force between 2 elements of current.

International Conference on Physics, Lond. 1934. International Union of Pure and Applied Physics and the Physical Society. PAPERS and DISCUSSIONS, 2 v., published by the Physical Society, Lond.; printed at the University Press, Cambridge (England) 1935. illus., 10x7 in., cloth, v. 1, 257 p., $3.20; v. 2, 183 p., $3.20. Papers and discussions presented at the conference. Volume one is devoted to nuclear physics and volume 2 to the solid state of matter, and include quantum electrodynamics, natural beta-decay, artificial radioactivity, the disintegration and synthesis of nuclei and elementary particles, cosmic radiation, the structure of molecules and of the ideal lattice, the deviations of real crystals from the ideal lattice structure, and plasticity and strain hardening in crystals.

DESCRIPTIVE GEOMETRY. By F. W. Bubb. N. Y., Macmillan Co., 1935. 234 p., illus., 9x6 in., cloth, $2.50. A method of presenting the subject in which the student is first taught to solve problems in space by the use of "fundamental space operations"; after which attention is first turned to 2-dimensional methods of showing these solutions.

A.S.T.M. STANDARDS on PRESERVATIVE COATINGS for STRUCTURAL MATERIALS (Paints, Varnishes, Lacquers and Paint Materials), prepared by Committee D-1 on Preservative Coatings for Structural Materials. September, 1935. Phila., American Society for Testing Materials. 387 p., illus., 9x6 in., paper, $1.75 ($1.50 to A.S.T.M. members). A compilation of specifications and methods of tests approved by the society.

ABSOLUTE THERMISCHE DATEN und GLEICHGEWICHTSKONSTANTE. By R. Doczekal and H. Pitsch. Vienna, Julius Springer, 1935. 69 p., illus., 9x6 in., paper, 6.60 rm. Collects and compares the measurements of specific heats and of heats of transformation, fusion, and vaporization which are scattered throughout the literature.

FACTORY EQUIPMENT. By J. W. Roe and C. W. Lytle. Scranton, Pa., International Textbook Co., 1935. 517 p., illus., 9x5 in., lea., $4.00. A survey of modern machine tools to aid selection or application for economic production.

FIRST COURSE IN DIFFERENTIAL EQUATIONS. By N. Miller. Oxford, Eng., Oxford Univ. Press; N. Y., Oxford Univ. Press, 1935. 148 p., illus., 9x6 in., cloth, $2.50. Aims to give an account of the most useful methods for solving differential equations, and to provide material for practice in them.

INTRODUCTION to ATOMIC PHYSICS. By J. Thomson. Lond., Methuen & Co., 1935. 228 p., illus., 9x6 in., cloth, 10s 6d. Covers the fundamental facts and theories and the more important experiments, and applies the theory to questions of atomic, nuclear, and molecular radiation.

INTRODUCTION to the THEORY of FUNCTIONS of a COMPLEX VARIABLE. By E. T. Copson. Oxford (Eng.), Clarendon Press; N. Y., Oxford Univ. Press, 1935. 448 p., illus., 9x6 in., cloth, $8.50. Contains an exposition of the properties of one-valued differentiable functions, and discusses the problem of conformal representation, the elements of the theory of integral functions, and the behavior of some of the special functions of analysis.

MATERIALS TESTING, Theory and Practice. By I. H. Cowdrey and R. G. Adams. 2 ed. N. Y., John Wiley & Sons, 1935. 144 p., illus., 9x6 in., cloth, $1.75. Provides a discussion of the methods commonly used for testing and of the fundamental principles involved.

REDUCING INDUSTRIAL POWER COSTS. By D. M. Myers. N. Y. and Lond., McGraw-Hill Book Co., 1935. 378 p., illus., 9x6 in., cloth, $4.00. Discusses the questions involved in the supply and use of steam and power from the economic point of view.

PRAKTISCHE PHYSIK. By F. Kohlrausch. 17 ed., edited by F. Henning. Leipzig and Berlin, B. C. Teubner, 1935. 958 p., illus., 9x6 in., cloth, 32 rm. (25% discount in U.S.A.) A revised edition of a reference book intended especially for those engaged in research work in pure or applied physics.

STRENGTH of MATERIALS. By E. R. Maurer and M. O. Withey. 2 ed. N. Y., John Wiley & Sons, 1935. 382 p., illus., 9x6 in., cloth, $3.50. A revised edition which includes an article on welded joints.

A.S.T.M. STANDARDS on ELECTRICAL INSULATING MATERIALS. Prepared by Committee D-9 on Electrical Insulating Materials. Specifications, Methods of Testing. Phila., American Society for Testing Materials, September 1935. 311 p., illus., 9x6 in., paper, $1.75. The report of the committee with the standard and tentative methods of testing these materials and the standard specifications for them, representing the latest revisions.

ALTERNATING CURRENT MACHINERY. By J. M. Bryant and E. W. Johnson. N. Y. and Lond., McGraw-Hill Book Co., 1935. 790 p., illus., 9x6 in., cloth, $6.00. A text for students of electrical engineering which presupposes a knowledge of the theory of a-c circuits. An extensive theoretical and practical treatment of apparatus is given in which the economic viewpoint is emphasized.

COMMUNICATIONS RADIO-ÉLECTRIQUES. Fascicule I. By H. de Bellescize. Paris, Gauthier-Villars, 1935. 98 p., illus., 10x7 in., paper, 20 frs. Discusses the nature of certain problems of radio communication which still await solution and suggests lines for attacking them.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Insulator Plant Reopens.—The insulator plant of the Ohio Brass Co. at Barberton, O., which was closed for some weeks due to labor difficulties, was reopened on December 23, and all departments have resumed normal operation.

Outlook for 1936.—Gerard Swope, President of the General Electric Co., looks forward to a continued improvement in business during 1936. Mr. Swope also stated recently that the volume of electrical manufacturing business in 1935 was approximately 30 per cent greater than in 1934, which was about the same increase as was shown for 1934 over 1933. Consumption of electricity in the United States was the greatest in the history of the country, being about 7 per cent more than in 1934 and 3 per cent more than in 1929, the previous peak year, due largely to increased use of electrical appliances in the home. Orders for capital goods in the electrical manufacturing industry have not increased to any great extent, because of the difficult position of the public utilities and transportation companies throughout the United States. Practically the only increase in the production of capital goods has been brought about by the modernization of industrial plants. Successive increases in the use of electricity, however, must eventually mean an increase in the generating capacity of public utilities, which will bring an increase in orders for capital goods to the electrical manufacturing industry.

Underwriters' Laboratories Moves New York Office.—No longer at 109 Leonard St., New York City, after a tenancy of 13 years, the Underwriters' Laboratories are now located at 161 Sixth Ave. where, in new quarters, the work of formulating standards and conducting tests on electrical appliances will be continued. Manufacturers, inspectors, and all who look to the Laboratories to aid in maintaining a high standard in the industry will appreciate the improved facilities of the new location.

1935 Lamp Sales Set New Record.—A new volume record in the annual sale of both large and miniature incandescent lamps was set in the United States during 1935, according to a review of the electrical industry prepared by John Liston of the General Electric Co. A preliminary estimate of the number sold indicates a total of 707,000,000, an increase of more than 11 per cent over the 1929 total of 634,233,000, the previous high total. The 1935 estimate includes 410,000,000 large and 297,000,000 miniature lamps.

New Carbon Resistor.—The Aerovox Corp., 82 Washington St., Brooklyn, N. Y., has developed an entirely new type of carbon resistor, to meet the most critical specifications for non-inductive resistors, particularly in the high-gain amplifying circuits. Of the solid molded type, the new Aerovox carbon resistor is plain, neat, compact, inexpensive. The special molded body is unaffected by humidity changes. It is non-inductive, with no appreciable resistance change at high frequencies; absolutely noiseless and permanent, on and off full load. A slight positive temperature coefficient is just sufficient to compensate minimum potential coefficient and to protect the unit against heavy short-period overloads. Electrically and mechanically rugged, each unit has stiff pigtails firmly soldered to the carbon resistor element.

New Western Electric Publication.—The first issue of a new magazine named "Pick-Ups" has been issued by the Western Electric Company. The introductory editorial states that the magazine will be devoted to "news of developments in the field of sound, and of the organizations and men who use the equipment designed by Bell Telephone Laboratories, manufactured by Western Electric and distributed by Graybar." In this initial number there are 26 pages with a two-color cover depicting the new non-directional dynamic microphone. Leading stories deal with the microphone, WTCN's new 5,000 watt station at Minneapolis, new radiophone equipment for aviators, the work of Bell Laboratories, a two-way ultra-high frequency police radio installation at Evansville, Indiana, and the wide-range public address system at the California Pacific International Exposition. The entire issue is copiously illustrated. The publication will be issued several times a year and will be circulated chiefly to users of Western Electric equipment such as broadcasting stations, police departments, and air transport companies, as well as to prospective users. The editor is Will Whitmore, and the assistant editor is M. M. Beard, both of the Company's headquarters staff at 195 Broadway, New York.

Trade Literature

Relays.—Catalog, 28 pp. Describes relays, timing devices, thermostats, resistors, thermal links, insulators, etc. Struthers Dunn, Inc., 129 N. Juniper St., Philadelphia, Pa.

Tantalum.—Bulletin, 48 pp. Describes the characteristics and applications of tantalum to a steadily increasing range of industrial uses. Fansteel Metallurgical Corp., North Chicago, Ill.

Speed-Measuring Instruments.—Bulletin 1435, 8 pp. Describes various types of tachometers and speed measuring instruments, including Frahm vibrating-reed hand tachometers. James G. Biddle Co., 1211 Arch St., Philadelphia, Pa.

Electrical Measuring Instruments.—Broadside E. Describes a comprehensive line of instruments for measurements in the laboratory, plant or field, and used in research, teaching, and testing. Leeds & Northrup Co., 4934 Stenton Ave., Philadelphia, Pa.

Connectors.—Catalog 33C, 48 pp. Describes a wide variety of electrical connectors in copper and aluminum for cable, tube, wire, bar, and rod. Illustrates applications of different types of these devices. Burndy Engineering Co., Inc., 305 E. 45th St., New York.

Pyranol Transformers.—Bulletin GEA-2048, 8 pp. Describes transformers designed and built to utilize Pyranol (non-inflammable and non-explosive) instead of oil. According to the publication there are now more than 250 Pyranol units installed, in sizes from 5 kva to 5,000 kva, and giving excellent service. General Electric Co., Schenectady, N. Y.

Pumps.—Bulletin 2206, 4 pp. Describes large, low head, double suction, single stage Type S pumps. Bulletin 2207, 4 pp. Describes large, high head, double suction, single stage Type S pumps. Bulletin 2208, 4 pp. Describes small, double suction, single stage pumps. Bulletin 2210, 4 pp. Describes Type M, multi-stage, double suction pumps. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Controlled Rectifiers.—Bulletin 8601. Describes controlled rectifiers, a new development, to supply a d-c output from a commercially constant, single-phase, a-c line. The output voltage regulation is plus or minus 2 per cent from approximately one-tenth to full load. On all sizes that cover a range from 30 watts to 250 watts, the efficiency is better than 50 per cent and the power factor better than 65 per cent. Ward Leonard Electric Co., Mt. Vernon, N. Y.

Insulators.—Bulletin, 8 pp. Describes a new series of improved, low voltage insulators, designed to increase the reliability of distribution and rural service, and reduce construction, maintenance, and replacement costs. Among the advantages claimed for the new insulators are that they are easier to handle and install; made with standard pin holes so that no expenditure for pins is necessary when used as replacements; designed so that the conductor is high above the top skirt; and they take a wide range of conductor sizes, making special insulators unnecessary. Locke Insulator Corp., Baltimore, Md.

Vibration Counter for Transmission Lines. Folder. Describes 2 new instruments, vibration counters, for frequencies between 4 and 100 per second. No. 514, weighing less than a pound, is clamped to the conductor. Its registrations can be read from the ground with binoculars. Vertical vibrations from 7 mm up and of any frequency over 4 per second are registered cumulatively. No. 515 is used for counting vibrations and for computing their frequency. This reads in units of single vibrations. Either type can be used as a counter for total number of rapid motions, in a great number of tests, such as fatigue, breakdown, etc. R. W. Cramer & Co., 67 Irving Pl., New York City.